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PROCEEDINGS OF THE DoD WORKSHOP ON THE MANUFACTURING/PRODUCIBILITY OF ORGANIC MATRIX COMPOSITES

(Held in Arlington, Virginia on 12-14 April 1988)

John E. Hove
William S. Hong
Stanley L. Channon
Editors

June 1989

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This document summarizes the findings of a 1988 DoD Workshop concerned with enhancing the production of organic matrix composites (OMCs) for use in the aerospace industry. Present barriers to the greater use of these performance-enhancing structural materials are dominated by a reliance on expensive, labor-intensive manufacturing methods. Higher costs associated with OMCs relative to conventional aluminum alloys were also traced to conservative design approaches (taking inadequate advantage of superior OMC properties), the lack of standardization for materials, processing and testing, a lack of domestically sourced raw materials or precursors, and tooling and capital equipment technology inadequate for high rate production.

Recommendations for changing the present situation are given which would affect all stages of the design and manufacturing process for OMCs. These include new design philosophies and worker training programs redirected for greater acceptance of OMCs, continued development of both raw materials and processing technques with automation in mind, standardization of appropriate aspects of the technology, and increased use of computer aided manufacturing and tooling appropriate for automation. The steps required for implementing most of these recommendations are discussed in greater detail.

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PREFACE

The production of advanced aerospace systems currently under development will be dependent on the availability of components manufactured with organic matrix composite materials. The Department of Defense has expressed concern over the supply of such composite materials and the ability of industry to meet anticipated needs.

The material supply issue is being addressed by the establishment of domestic facilities for production of carbon fibers, which, up to now, have been strongly dependent on foreign sources of precursor supply.

The manufacturing issue is not being addressed on a broad front. Although the armed services are addressing their generic and specific manufacturing problems through the DoD Manufacturing Technology (MT) program, an overall, coordinated national program needs to be established.

The DoD decided that a workshop should be conducted to address the composites manufacturing issue. The ultimate goal of the workshop was to increase national production efficiency and capability for manufacturing composites sufficient to provide the required domestic industrial base for defense systems identified for production in 1995. This would be achieved through new cost-reducing materials and improved manufacturing technology. The purposes of the workshop were to identify and recommend areas of composite manufacturing development and related technologies needed to provide the industrial base for future weapon systems, and to identify and recommend management and program initiatives to achieve the stated DoD goal. Key personnel from industry and government were to address the workshop goal and purposes.

The workshop, named the DoD Composites Manufacturing, Producibility, and Affordability Workshop, was held 12-14 April 1988 in Arlington, VA. This report documents the results of the workshop.

ABSTRACT

This document summarizes the findings of a 1988 DoD Workshop concerned with enhancing the production of organic matrix composites (OMCs) for use in the aerospace industry. Present barriers to the greater use of these performance-enhancing structural materials are dominated by a reliance on expensive, labor-intensive manufacturing methods. Higher costs associated with OMCs relative to conventional aluminum alloys were also traced to conservative design approaches (taking inadequate advantage of superior OMC properties), the lack of standardization for materials, processing and testing, a lack of domestically sourced raw materials or precursors, and tooling and capital equipment technology inadequate for high rate production.

Recommendations for changing the present situation are given which would affect all stages of the design and manufacturing process for OMCs. These include new design philosophies and worker training programs redirected for greater acceptance of OMCs, continued development of both raw materials and processing techniques with automation in mind, standardization of appropriate aspects of the technology, and increased use of computer-aided manufacturing and tooling appropriate for automation. The steps required for implementing most of these recommendations are discussed in greater detail.

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EXECUTIVE SUMMARY

A. INTRODUCTION

Organic-matrix composite (OMC) materials of various types are gaining popularity in weapon systems development as a means of reducing system weight and increasing system performance, especially in airborne systems. Current designs of advanced military aircraft use OMCs in as much as 50 percent of the structural components. Although the applications have increased rapidly during the past two decades, current production methods are still highly labor-intensive, with limited capability for accelerated production in periods of emergency. In addition, the most commonly used reinforcing fiber, carbon, has been largely dependent on foreign sources of starting material, further limiting the ability to expand U.S. production of composite components for military systems.

Previous workshops[1] have addressed concerns over the lack of domestic sources of materials and the high cost of qualification of materials and products. The current workshop focused on the problems and opportunities relating to increasing domestic production of composites through improved manufacturing methods and producibility considerations, including the need for automation and computer-aided controls.

B. WORKSHOP FORMAT

The workshop was held at the National Clarion Hotel, Arlington, VA on April 12-14, 1988. The format was developed by a steering committee consisting of representatives from DoD (OUSDA), the armed services, and the Institute for Defense Analyses. Four working groups were formed, each with a aervice chairman, an industry cochairman, and up to 25 specialist participants from industry and government. Attendance was limited to U.S. citizens. The working groups were divided as follows:

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1 See, for example, "Proceedings of Colloquium/Workshop on Composite Materials and Structures: Standardization, Qualification, Certification," Stanley L. Channon, Editor, IDA Record Document D-70, July 1984.

1. Design
2. Materials and Processes
3. Tooling
4. Lay-up and Assembly.

A fifth working group on Testing and Inspection was originally planned but was not formed (see Appendix A) because of a recent broader workshop on that subject, as reported in an IDA document.[2]

Each working group spent two days discussing the issues and preparing recommendations. On the third day, each chairman presented a summary of the group's findings and recommendations. Editing and summarizing of the Proceedings was performed by the Institute for Defense Analyses.

It is recognized that there is a great deal of unavoidable overlap among these working groups. However, no harm results and there is some advantage to be gained from examining some subjects from various viewpoints.

C. COMPOSITE STRUCTURES MANUFACTURING CYCLE

The steps involved in manufacturing organic composite structures are schematically summarized in Fig. 1. Reinforcement materials supplied by different sources for a variety of applications are brought together to produce a "prepreg" material which can be readily handled in the lay-up and assembly operations. Structural design dictates the optimum fiber orientation to withstand the service loads; however, the ideal fiber placement is generally limited by practical restraints on available weaving or other placement equipment. Stacking of several plies of material in a predetermined sequence can reduce this limitation to some extent. Tooling materials play an important part in the manufacturing cycle since the tool surfaces must have long life, easy maintenance, low cost, and be capble of providing the precise profile for the component configuration without distortion. Curing of the organic matrix material is a complex procedure involving a delicate application of pressure and heat, either in a large autoclave or in specially designed and dedicated unit tools. The assembly of subcomponents into the final product may be accomplished by mechanical fastening, adhesive bonding, or co-curing.

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2 "Summary Record of the 1988 Meeting of the Ad Hoc Working Group on Nondestructive Evaluation (NDE)," Richard T. Loda, Editor, IDA Memorandum Report M-474, July 1988.

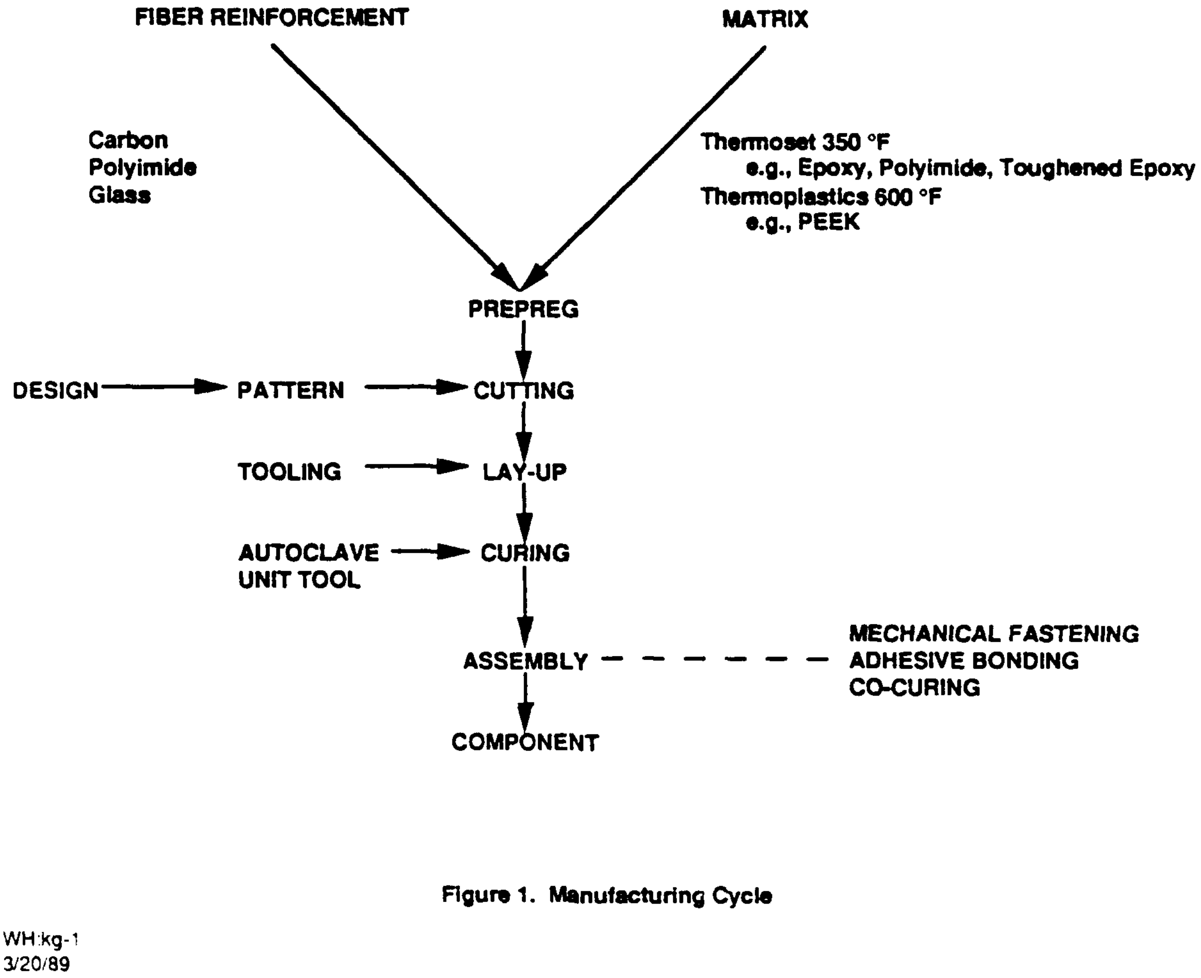

Figure 1. Manufacturing Cycle

Some of these manufacturing steps have been partially automated, but manual labor is still the predominant method of manufacture. Strong dependence on skilled labor results in irregularities in quality which can be magnified by inadequate training of production employees.

D. LIMITATIONS TO HIGH-RATE PRODUCTION

Composite materials are unique in that the material is formed during the fabrication of the component, whereas metallic structures are generally produced by the shaping or machining of consolidated forms.

A number of inherent limitations exist in the production cycle which are impediments to high-rate production. The form in which the material is supplied can vary considerably, ranging from unidirectional tow or tape of fibers with different yarn counts, thicknesses, and widths to woven broad goods of different weaves, widths, thicknesses, and fiber orientation. Multiple steps are involved in laying out, cutting, and compiling kits of patterns prior to placement of the materials in the desired configuration. While much effort has been devoted to automation of these operations, automation is still not widely used.

Tooling design and fabrication concepts involve several intermediate steps which add to the cycle time for tool manufacture. The wide variety of tool configurations required for several small components also limits the production rate.

One of the principal advantages of composites is that components can be designed with fibers oriented in desired directions, but in complex configurations, this may be difficult to accomplish by high-rate production methods. Design for high-rate production therefore requires compromises in the ideal fiber geometry. Transition from thin to thick sections in the same component also requires special attention and limits the production rate.

The curing operation is based on the component configuration and type of matrix systems being cured. While autoclaves are still commonly used because of their size and ability to accommodate a variety of shapes in a single load, the loading of autoclaves is limited by the resin system, part thickness, etc. Large autoclaves generally require longer heating cycles, although larger loads can be accommodated.

Testing and inspection of components, as well as process control throughout the fabrication cycle, also tend to limit production rates. Methods for high-rate testing and process control are not well developed.

E. WORKSHOP FINDINGS

1. System Performance Has Been the Primary Concern in OMC Applications

Once the properties of OMCs became known and accepted by industry and government, emphasis was focused on improving system performance of military aircraft hardware. The weight savings offered by composites provided a strong incentive to increase payloads or extend the range in weapon systems. Important considerations of producibility, maintainability, and affordability were essentially bypassed. Now that OMC stru tures have proven their worth in systems, attention needs to be focused on the other factors which will determine their long-range acceptance.

2. Design Approaches With OMCs Have Been Conservative

It is generally conceded that the design of composite structures has been hampered by following the design philosophy associated with metal structures, whose properties are more nearly isotropic. Full advantage has not been taken of the benefits to be derived from the use of composites. Also, full advantage has not been taken of advances in materials development because of restrictions in systems development programs which minimize risk by using only state-of-the-art materials. For the same reason, new materials developments are not proven because the development periods for demonstration are not compatible with the system development and production schedules.

Automation has not been a primary driving force because production rates in the past have been relatively low.

There are uncertainties about the effects of defects in composite structures, which tend to force designers to take a conservative position. Tolerances on dimensions and defects are generally considered to be unrealistic.

3. OMC Design Data are Limited

As a result of the continual evolution of composite materials, very few have reached the level of consistency and reproducibility required for quality high-rate production.

Furthermore, consumers (systems development organizations) generate design data on a specific material for a specific application and tend to retain the data as proprietary information. Pooling of data from various sources is seldom satisfactory because of differences in material form and testing methods. This situation is particularly prevalent among the thermosetting resin systems. Design data on the recently developed thermoplastic resin composites is practically nonexistent.

4. Component Development Cannot be Conducted in Production

Attempts to develop composite components as part of production programs have been unsatisfactory. Production schedules do not allow sufficient time for proper development with minimum risk. Yet, development must be undertaken on high-risk materials in order to improve weapon systems capabilities. To provide the proper environment, component development should be related to but decoupled from the production program. (Note that this has overtones of the concurrent design concept which is gaining attention within DoD circles.)

5. Manufacturing Equipment Development Needed for High-Rate Production

Production equipment development is frequently associated with production programs without benefit of prototype development, resulting in less-than-optimum production facilities. As in the case of component development, time must be allowed for equipment development prior to production. While universal equipment is desirable, special equipment will be required for some advanced materials. Demonstration of producibility is essential before putting newly developed equipment into production.

6. Domestic Sources, Standardization, and Cost Reduction of Materials are Needed

As pointed out in previous studies, there is strong reliance on foreign sources for some materials involved in composites manufacture. While steps are being taken to reduce this dependence, there is a need for qualification of sources. Present procedures involve separate qualification of a given material by each individual program, resulting in much unnecessary duplication and added cost.

Some degree of standardization of materials, test methods, qualification criteria, and product forms should reduce overall material costs and enhance producibility. Action is needed in all of these areas.

7. Labor-Intensive Operations Require Personnel Training

Many steps in the manufacturing of composites hardware, now performed manually, could be improved through automation. However, manual labor may be most efficient and practical for highly contoured components which do not lend themselves to automation. In these cases, automation of the preliminary steps, such as cutting and kitting, may greatly reduce the subsequent manual operations, needed to ensure quality control and producibility. The dependence on manual labor creates the need for training skilled personnel, which may take many years. At present, there are no standardized criteria for qualifying composites production workers, either for tooling manufacture or material handling.

8. Inspection and Quality Control Criteria Are Not Well Established

There is still much manual labor involved in inspection and quality control, using techniques which require interpretation by individuals. For high-rate production, emphasis should be placed on the development of in-process inspection techniques and acceptance criteria to reduce the human element.

9. Tooling Materials and Concepts Need Refinement

Many materials and tooling concepts have been developed by manufacturers, based on their experience in producing certain types of components. Current tooling approaches require many intermediate steps to produce the final tool, adding to the cost. High-rate production tooling may require refinement of tooling materials and concepts to ensure high quality reproducible components.

Secondary tooling materials, such as vacuum bags, sealants, bleeder cloths, etc. are critical items in composite manufacture and can become critical in high-rate production.

The trend toward resin systems with higher curing temperatures leads to the requirement for higher temperature tooling materials which will maintain their configurations.

10. Curing is a Major Impediment to High Rate Production

There is high reliance on the autoclave for curing organic composites, due to its flexibility and ability to accept large mixed loads. However, the long cycle times associated with this type of curing facility are a serious obstacle to high-rate production unless additional equipment is added. Independently heated and pressurized curing tools are also available but must be manually loaded and unloaded.

Production rates could be increased significantly if rapid curing resins which do not require autoclaves were available.

F. RECOMMENDATIONS

1. Enhance Training Programs

Adequate training for engineers, designers, manufacturing, tooling, and quality control personnel needs to be emphasized. Interaction between the various disciplines involved in manufacture of composites is essential and methods should be developed to ensure this interaction. In addition, the semi-skilled labor force needs extensive on-the-job training to become proficient in the various steps involved in composites manufacture. While this need seems obvious, it will not be easy to implement. A separate and more detailed study should be made of this important topic.

2. Develop Improved Materials Tailored for Automation

Materials suppliers should be encouraged to reduce the cost of materials through innovative processing. They may also provide materials in kit form as near-net-shape preforms to reduce operations at the fabricator. There is also a need for resins which cure rapidly, at low pressure and preferably at low temperature. Resins with tailored cure rheology would allow them to be used in a "lay-up to full consolidation" process. The advantages of thermoplastic resin systems need to be exploited further by development of resins with lower melt temperatures and viscosities.

3. Develop Improved Processing Techniques

In conjunction with the development of improved resins, improvements in processing methods should be undertaken to take advantage of the rapid-curing or low-pressure curing systems. Also, attention should be paid to the development and use of intermediate products such as pultrusions, braided forms, and standard structural sections.

The use of monitoring devices to control the processing is also a part of the process development. Control criteria need to be developed in conjunction with the design requirements and manufacturing equipment capability.

4. Develop Prototype Equipment Before Starting Production

Higher rate production equipment for any given system requires a period of development and redesign before being placed in service. Equipment manufacturers should be involved at the initial stage of component design to provide practical guidance on equipment limitations. In addition, special processes and equipment need to be developed for small components.

It is strongly recommended that equipment development be recognized as an important prerequisite to production and that it should be undertaken as a separate and distinct entity with appropriate funding provided. Part of this effort should consist of a demonstration through manufacture of one or more typical components.

5. Standardize Certain Elements in Composites Technology

To increase the use, reduce the cost, and improve the reliability of composites, certain parts of the composites technology need to be standardized, especially materials and product forms, test methods, qualification procedures and criteria, and design data. Standardization is also needed for high-rate production. Such an effort requires the cooperation of suppliers, fabricators, and users.

6. Develop Design Philosophy Appropriate to Automation of Design and Manufacture of Composites

Design options of sheet/stringer, sandwich, or composite laminates for lightweight structures should be given proper consideration through trade-off studies before committing to any particular design philosophy for production. New approaches need to be developed to provide corrosion resistance and impact damage resistance in some composite designs.

In high-production-rate processes, it is imperative that the design be developed to provide automation of manufacturing, quality control, and inspection.

7. Exploit Use of Computer Technology in All Aspects of Composite Design, Manufacture, and Testing

Computer assistance should be fully utilized in the design of optimum structural integrity, producibility, development of fiber placement procedures, layout, cutting and sequencing of plies, control of curing, development of tool design, inspection methods, and many other applications.

8. Develop Acceptance Criteria

Programs on the effects of defects on the performance of composites should be conducted by major industry groups teamed with the academic community.

9. Improve Tooling Design

Tooling design should be directed toward the use of fewer tools, better materials, and simpler fabrication and assembly operations.

I. INTRODUCTION

A. BACKGROUND

The manufacture of structures with organic-matrix composite (OMC) materials has developed gradually from an art form to a semi-scientific endeavor over the past quarter of a century. However, many of the manufacturing operations are still labor intensive, with resulting high costs and low production rates. The many steps involved in manufacturing organic composite structures are schematically summarized in Fig. 1 (in the Executive Summary), which does not include the preliminary steps associated with the production of fibers and matrix materials from which the composites are fabricated. This summary also omits the various process controls and inspection steps that are essential to the manufacture of reliable composite structures.

For aircraft systems, OMCs offer higher performance capability through weight reduction and maintainability, resulting in a more efficient defense arsenal. This performance advantage is achieved through design approaches which optimize the integrity of the composite structures by placement of reinforcing fibers in preferred locations and directions in the structure. Ideal fiber placement must often be compromised by limitations on producibility, especially if automation is used. Some structural configurations are very complex, consisting of convex and concave surfaces and transitions from curved to flat surfaces. Such structures are not readily amenable to automation and would have to be redesigned to be compatible with high-production-rate automated equipment. These complexities emphasize that the design and producibility of composites are interdependent.

Tooling and equipment design are also closely related to the component design and are potential limitations to high-rate production. These areas are therefore an integral part of the design and manufacturing planning process.

Another important consideration in high-rate production is the composite material itself. The currently available materials are generally compatible with batch-type manufacturing operations or low-volume automated processes. Modifications in material form and condition will undoubtedly be required for high-rate production.

Recognizing the importance of these interacting areas, the Department of Defense identified the need for a workshop in which these key subjects would be addressed by selected specialists in each phase of the technology. From the results of the workshop, it was expected that a number of specific recommendations would emerge which would provide the basis for further action to enhance the capability for manufacturing reliable composite materials and structures.

B. WORKSHOP FORMAT

The workshop was held at the National Clarion Hotel, Arlington, VA, on April 12-14, 1988. The format was developed by a steering committee consisting of representatives from DoD (OUSDRE), the DoD Manufacturing Technology Advisory Group (MTAC), and the Institute for Defense Analyses.[3] Four working groups were formed, each with a service chairman, an industry cochairman and up to 25 specialist participants from industry and government. Attendance was limited to U.S. citizens. The working groups were divided as follows: names of the chairman and cochairman are in parentheses (affiliations and addresses are listed in Appendix B):

1. Design (Larry Kelly and Charles Rogers)
2. Materials and Processes (Charles Browning and Flake Campbell)
3. Tooling (David Beeler and Cecil Schneider)
4. Lay-up and Assembly (Thomas Mazza and Robert Anderson).

A fifth working group on Testing and Inspection was originally planned but was not formed because of a recent broader workshop on that subject. A test and inspection committee was formed, however, to report on quality issues that emerged, and to relate them to the results of the previous workshop.

Each working group spent two days discussing the issues and preparing recommendations. On the third day, each chairman presented a summary of the group's findings and recommendations, and the test and inspection committee presented a summary of their findings and recommendations (see Appendix A). Assembly and editing of the Proceedings was performed by the Institute for Defense Analyses.

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3 (See Appendix B). The Chair for both the Workshop and the Steering Committee was Ferrel E. Anderson, Chairman of the DoD MTAC Nonmetals Subcommittee.

It is recognized that there is a great deal of unavoidable overlap among these working groups. However, no harm results and there is some advantage to be gained from examining some subjects from various viewpoints.

C. LIMITATIONS TO HIGH-RATE PRODUCTION

Composite materials are unique in that the materials are formed during fabrication of the components, whereas metallic structures are generally produced by shaping or machining of consolidated forms.

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Tooling design and fabrication concepts involve several intermediate steps which add to the cycle time for tool manufacture. The wide variety of tool configurations required for several small components also limits the production rate.

One of the principal advantages of composites is that components can be designed with fibers oriented in desired directions. But, in complex configurations, this may be difficult to accomplish by high-rate production methods. Design for high-rate production therefore requires compromises in the ideal fiber geometry. Transition from thin to thick sections in the same component also requires special attention and limits the production rate.

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Testing and inspection of components, as well as process control throughout the fabrication cycle, also tend to limit production rates. Methods for high-rate testing and process control are not well developed.

II. WORKING GROUP REPORTS

A. DESIGN PANEL

The Design Panel addressed a number of areas, ranging from design philosophy to standards. The design of composite structures is a balance of many constraints. For many years, the emphasis has been on weight, performance, and affordability; now, producibility is being given more consideration. The designer also finds himself in the difficult position of having to choose between proven state-of-the-art materials and design approaches and the more advanced, higher risk materials and design philosophy. Standards of acceptance for materials, manufacturing tolerances, and structural defects are generally not available or not specified clearly enough to permit optimization of designs. These and other design-related considerations are discussed in the following sections.

1. Freedom of Structural Choice

An important structural concept for secondary and primary aircraft structure applications is sandwich construction. One primary motivation for development of sandwich structure has been the significant decrease in the number of parts required over that of conventional, mechanically fastened construction. However, the experience of DoD maintenance personnel with early bonded sandwich construction indicates that service reliability is poor because of disbonding, moisture intrusion, internal metal corrosion, and inspection and resealing problems, which result in costly repairs. Thus, there has been a movement away from sandwich structure and honeycomb in particular. This warrants re-examination, since sandwich construction can be the most structurally efficient design approach for many applications.

The latest generation of structural adhesives and the broad technology base that supports them, including laboratory test procedures that correlate well with service experience, indicate that structural adhesive bonding can be as reliable as conventional mechanical attachment. Thus, the current avoidance of adhesive-bonded structures and concern over the reliability of bonded joints and sandwich construction is unwarranted.

Moisture intrusion and its impact on sandwich structure is a long-term problem. The demonstration of successful flight service experience requires several years of in-service data. Validation that the new adhesives, bonding techniques, and acceptance criteria for sandwich construction have indeed eliminated the maintenance problems of the past will require a long-term, comprehensive hardware demonstration program.

Recommendations

DoD needs a concentrated, long-term effort to remove the stigma associated with bonded sandwich construction. Such an effort would consist of the following phases.

Phase I--Collection of field service data to clearly define the problems, causes, and effects. This would be a complete survey and compilation of service histories, design details, and processing methods. This survey should include civilian, commercial, and military applications, and maintenance facility experience. The result of this analysis would be a major "lessons learned" publication/workshop forum.

Phase II--Characterization of new sandwich materials and adhesives. Laboratory verification of corrosion resistance, impact damage tolerance, moisture insensitivity, and overall improved durability.

Phase III--Field inspection and tracking of a large number of improved sandwich components installed side by side with early sandwich structures.

Estimates of costs and time needed to carry out these three phases are shown in Fig. 2.

2. High Payoff Design Concepts

The ability to reduce costs can be significantly influenced early in the design process. As programs progress and production decision points are reached, however, excessive risk exist in cost and scheduling if technology other than that which has already been proven through research, development, demonstration and validation programs is employed. As a result, many current composite designs use "black aluminum," that is, graphite material which replaces metal as a design substitute. Optimally designed composite structures that are both structurally more efficient and more cost effective than "black aluminum" designs are often too high risk to pursue in production. One such

PHASE	COST	DESCRIPTION	SCHEDULE (YEARS) 1 – 4
I	300,000 to 500,000 Dollars	Service history, design criteria, application review.	WORKSHOP; RECOMMENDED PROJECTS
II	1.5 Million to 2.5 Million Dollars	Design development,[1] subcomponent testing, certification process definition.	SELECTED APPLICATIONS; DESIGN REVIEW/ IMPLEMENTATION PLAN; SUBCOMPONENT FABRICATION/TEST COMPLETE
III	4 Million to 6 Million Dollars	Full-Scale Development	FABRICATION[2] COMPLETE; STATIC TEST; CERTIFICATION

[1] Primary Design constraints/criteria from selected project

[2] Two to three test articles

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Figure 2. Phased Program for Sandwiched Composites

concept is "Unitized Design" which offers significant cost gains by reducing labor intensive steps and individual subcomponent tooling. This concept integrates innovative design ideas with innovative manufacturing approaches that are only possible outside a weapon system development activity. These ideas need to be studied in parallel or possibly in a preproduction, preplanned risk reduction program for producibility enhancement.

A recent assessment[4] of composites state of the art conducted by the National Research Council concluded: "The full cost benefits of composites will not be realized until designs and manufacturing processes take advantage of the unique characteristics of composites and composite structures are not designed and built like metal structures. The government can accelerate this activity by soliciting and sponsoring research to identify new structural shapes, elements, and components that are amenable to low-cost manufacture." NASA's Langley Research Center has initiated just such an activity under a program titled "Advanced Composite Structural Concepts and Materials Technologies for Primary Aircraft Structures." The objective of this activity is to build the data base to allow designers to produce components and secondary and primary structures that could cost one half or less that of current aircraft structures.

Recommendations

1. Support development of new structural concepts and innovative manufacturing processes by supporting and fostering the NASA initiative.
2. Implement preplanned risk reduction prototype efforts that are outside the mainstream production activity, yet evaluated against a production design for realistic cost/weight benefit assessment for a specific vehicle application, e.g., a V-22 tape-wound aft fuselage manufacturing technology program.
3. Place the products of these efforts in flight service evaluation to assure that confidence levels are high enough for implementation in production contracts. A three-phase effort (Fig. 3) is proposed that proceeds from subcomponent to full scale development and addresses the critical issue of large, unitized components, namely, the scrap factor. An important part of Phase II is development of in-process defect repair to be traded against component size/cost and tooling concepts.

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4 Advanced Organic Composite Materials for Aircraft Structures - Future Program Committee on the Status and Viability of Composite Materials for Aircraft Structures, 1987.

PHASE	COST	DESCRIPTION	SCHEDULE (YEARS) 1 · 2 · 3 · 4
I	300,000 to 500,000 Dollars	Design alternatives, trade methodology, application review.	STUDY SYSTEMS SELECTED RECOMMENDED APPLICATIONS
II	3 Million to 5 Million Dollars	Design development, subcomponent tests, process development.	SELECTED APPLICATIONS DESIGN REVIEW[1] PROCESS SCALE-UP VALIDATED PROCESSES
III	6 Million to 8 Million Dollars	Full-Scale Development.	PROCESS SCALE-UP VALIDATED FABRICATION[2] COMPLETE

[1] Primary design, criteria supplied by project

[2] Process validation - ready for project implementation

Figure 3. Phased Program for Unitized Component Design

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3. Allowable Tolerances for Defects

The costs and rate of composite production are detrimentally affected by both stringent engineering requirements for initial quality and the demands for a full service life, even with the maximum expected service damage inflicted in the most critical area.

The art of fracture mechanics as applied to composite materials is gradually becoming a science. Analytical treatment of delaminations and microcracking has progressed in parallel with the development of tougher materials systems. Fracture work is beginning to pay off in the study of fiber rupture at stress concentration points such as holes. Significant progress has been achieved in determining the effects of interlaminar stresses. These achievements have not yet benefited the major DoD programs because the transition from theory and coupon data to large, highly critical components on sensitive programs is difficult. Production managers are more concerned with minimum risk than minimum cost, largely because of the type of contracts being negotiated.

Because of the nature of basic material and processing procedures, any manufactured composite product is likely to have one or more of the anomalies listed below:

- Incorrect overall fiber volume fraction
- Misaligned or broken fibers
- Non-uniform distribution of fibers
- Groups of fibers imperfectly wetted
- Gaps or overlaps in the arrangement of plies
- Inter-laminar debonded regions (delaminations)
- Incorrect state of resin cure
- Resin voids or transverse ply cracks.

Many of these anomalies are insignificant, while others may locally reduce the strength of the material below required component design stress levels. To apply fracture mechanics techniques to the analysis of such anomalies requires extensive data from comprehensive research efforts quantifying their effects. Until such data exists, conservative acceptance/rejection criteria will be employed. To overcome this conservatism, programs directed toward a determination of the "effect of defects" at the component level with a sound analytical base must be conducted.

Recommendations

1. Conduct "effect of defects" programs that are directed by the industry groups which have the application programs and thus the need, teamed with the academic community in order to assure an analytically based product instead of a purely empirical result.
2. Programs should be coordinated or solicited from each of the major contractors on the V22, LHX, AFT, and ATA programs. These programs should run concurrently with the design phase, extend over at least a two-year period, and require about a ten-man-year level of scientific effort.

4. Standard Composite Parts and Materials Process Specifications

Qualification of baseline materials for aircraft structure is very expensive. DoD cannot afford multiqualifications nor does it desire sole-source procurement. It is important to minimize material/product qualification requirements, yet enhance competition and availability of a wide variety of product forms.

Composite parts are largely constructed manually, although some portions of the process may be mechanized. The process requires close control of the span time due to the short working life of the material. Standards do not exist that would allow a prime contractor to spread production over the large "plastic" industrial base. Thus, the prime contractor is forced to make nearly all the parts of a vehicle, large or small, except that which is subcontracted to other large aerospace contractors. There is a large third level tier of competent suppliers who could supply smaller parts if they knew that qualifying to one manufacturer's requirements would also satisfy qualification requirements for others. This would require the development of standard material and qualification specifications.

The use of common specifications between companies and government agencies for specific weapon systems has resulted in substantial savings. To obtain similar benefits across a wide range of procurements, standards need to be developed for measurement, evaluation techniques, and specifically for material production processes so that a wide range of vendors can supply similar products. For example, many shapes, such as "T's", "I's" and even beads, corrugations, and angles could be manufactured to a prime contractor's drawing, specifying size, shape, and orientation if vendors were allowed to develop their own methods, providing they could qualify their product to a standard performance specification.

Recommendation

1. Leave detailed development of new materials, manufacturing processes, and applications to the materials industry working in concert with aircraft designers and manufacturers.
2. Concentrate government efforts on standards of measurement and material processing specifications. The product form and detailed geometry can then be specified by the user and several sources could compete for duplicative parts that are used in quantity.
3. A Military Specification should be prepared containing the performance requirements of the composite material from which a shape is to be made. Laminate strength, stiffness, and toughness requirements should be given. Specific treatment should be given to typical structural element problems such as corner beads, T intersections, and ply stacking stresses. Multiple contract awards should be made to second- and third-level manufacturers of aerospace composite products for the purpose of qualifying their products to the Military Specifications.

One could anticipate as many as a hundred responses over a five-year period. The average qualification cost might be on the order of $100,000.

5. Thermoplastic Materials Processing

Combining thermoplastic resins with intermediate modulus and/or high-strain fibers provides not only more structurally efficient and more damage-tolerant composites, but potentially the use of low-cost molding and forming processes. Thermoplastic resins have been utilized in such high-volume processes as injection molding, extrusion, and vacuum forming. Simply applying present thermoset design and manufacturing technologies will not yield the potential performance and cost advantages thermoplastics have to offer. Programs are needed that establish a data bank of thermoplastic material properties and processing techniques to allow designers to select with confidence a material/structural design concept and fabrication approach that advantageously utilizes traditional thermoplastic processing techniques.

The key to thermoplastic composite material utilization is production-qualified, low-cost processing, tooling, and general manufacturing approaches.

Recommendations

1. Develop a thermoplastic material manufacturing guide that delineates the advantages and disadvantages of the following processes:

- Hot head tape laying/placement
- Diaphragm forming
- Dusion bonding
- Adhesive bonding
- Press forming
- Filament winding
- Pultrusion
- Autoclave curing
- Reconsolidation.

2. Develop a thermoplastic material design guide that provides an engineering data base relative to the above processes and includes the following:
   - Engineering material data base
   - Chemical resistance (solvent sensitivity)
   - Repair/reconsolidation approaches
   - Joint design allowables (bolted, bonded, fused, welded)
   - Hot wet allowables/environmental resistance
   - Damage tolerance (fracture toughness data)
   - Creep and fatigue resistance.

6. Limited Autoclave Capacity

Use of autoclaves has historically been energy-, capital-, and labor-intensive, and due to the extended periods required for cure, a limiting factor in obtaining projected surge production rates. The present staging and curing processes for advanced composites are highly "energy intensive" because they take place at high pressure and temperature in autoclaves for long periods of time. However, the near-term elimination of autoclaves is not advisable or practical. Autoclaves permit fabrication of large unitized assemblies, produce consistently high quality parts (minimum porosity), and for most companies their cost has been amortized.

Non-autoclave cure processes have been shown to be five to ten times more energy efficient, and when carried out properly, produce quality parts equivalent to those cured in autoclave, as measured by porosity levels and interlaminar shear strength. This makes non-autoclave cure processing an ideal backup for surge requirements.

Recommendations

1. Expand manufacturing technology efforts for non-autoclave fabrication of composite structures to establish such processes as vacuum bag/oven cure, thermoforming, press forming, and self-contained tools as viable options to autoclave curing.
2. Fabricate and test significant numbers of full-scale *primary structure* components to establish the non-autoclave processing approaches as viable alternatives.

B. MATERIALS AND PROCESSING PANEL

The Materials and Processing panel addressed three key areas traditionally associated with the area of materials and processing:

- Material product forms
- Lay-up/materials placement
- Cure/consolidation/forming

The emphasis in the discussions was on how to achieve significant reductions in the cost of manufacturing composite parts; i.e., how to achieve significant improvements in composites producibility. The ability to provide surge capability in the event of a national emergency was also considered. The output of the panel was organized into four sections:

- *Issues* associated with achieving the stated objective
- *Recommendations* of actions that would address these issues
- A *roadmap* with program to attack those areas within the scope of the panel's charter
- A *descriptive write-up* that describes the key features of each of the roadmap programs.

A brief discussion of the key points associated with these issues follows.

1. Issues

Design Limitations--Today's designs are not driven by cost or producibility . Instead, they are primarily performance driven. This usually results in severe limitations being placed on manufacturing, often resulting in high-cost parts due to expensive tooling, high fabrication costs, long lead times, and excessive scrap and rework costs. Many "weight saving" designs become so complicated and difficult to build that they can never be automated. In addition, many designers are not familiar with designing parts for automated equipment, such as tape layers and filament winders.

Qualification Restrictions--The costs and timing associated with qualification requirements in today's production scenarios can result in severe limitations. These requirements can inhibit the acceptance of new materials and improved processes. They can essentially inhibit creativity and new approaches to lowering costs.

A related cost issue is that today's "accepted" materials can be qualified and requalified several times. This practice results in a "value added tax" being placed on each new composite production program. An additional concern is that once a material gains industry acceptance, it becomes extremely difficult for a new material to replace it.

Current Equipment Limitation--Today's product forms and laydown and/or placement equipment were developed and procured to be all things to all people. As such, they may not be superior (or even adequate) for any one specific task. Also, today's equipment may not be amenable to being reconfigured for innovative, low-cost processes. An additional observation is that as the equipment becomes more complex, the software required to drive it becomes as important as the actual hardware.

Materials Limitations--Several limitations have been imposed on our materials. Today's product forms tend to be limited to those that directly support accepted production processes. New materials that may have cost reducing features that require new processing methodologies are not readily accepted.

Today's materials may not have the characteristics to support low-cost production methods. Also, they may not have sufficient tolerances to be used in precision materials handling machines.

Today's resin technology is also a limiting factor in low-cost materials and processes. Current thermosets have rheological and gel properties, cure times, and use temperatures that will restrict significant advances in low-cost processes. Current thermoplastics have high melt temperatures and melt viscosities that will significantly limit low-cost improvements.

Materials capacity may eventually be the key factor limiting future surge capability. In particular, the carbon fiber capacity may not be sufficient to meet increased production rates.

Part Quality Standards--Today's quality standards for parts tend to be restrictive, very inconsistent, and not quantified. For example, the real impact of "defects" such as gaps, overlaps, voids, and porosity are rarely known. In order to be "safe," parts with even minor discrepancies are often rejected. Substantial costs are associated with the search for quality.

A substantial effort is devoted to NDI of parts. While many parts may be rejected, very few are ever scrapped. Most end up being used eventually.

Cost and Quality--The redundancy of testing can result in a substantial value added to the cost picture. Starting materials are tested by suppliers. Test results are provided to the users, who then repeat the same tests in their own facilities.

The following is a brief discussion of recommendations that address these key issues.

2. Recommendations

Design for Manufacturing--A key recommendation is that cross training between designers and manufacturing engineers be instituted. This would allow both parties to see what each is operating against.

More emphasis needs to be placed on manufacturing input to the design process, during both the conceptual and detail design phases. Computer simulation techniques need to be developed that will allow proposed designs to simulate the actual manufacturing processes that would be required to manufacture the proposed design. These simulations would allow trade-offs to be conducted to arrive at the optimum design from the standpoint of both performance and cost or producibility. More emphasis needs to be placed on producible designs by all involved: the customer, program management, engineering, quality, and manufacturing.

Materials Placement Equipment--Current lay-down equipment needs to be pushed to much higher rates. Today's rates are much too slow to significantly affect costs.

The development of new materials handling equipment should involve considerable prototyping. Past practices of jumping from blueprint to multimillion dollar production machines that are supposed to handle a multitude of tasks are too costly. Performance needs to be demonstrated at a prototype stage before committing to production. This prototype phase should include software as well as hardware development.

More emphasis needs to be placed on thermoplastic consolidation because of the great potential for lowering cost. Equipment needs to be developed that will allow this to take place in a low-cost, performance/design acceptable manner.

Innovative, low-cost processes for complex, labor intensive small parts needs to be developed and/or explored because of the extremely high cost per pound for manual fabrication. Examples would include resin transfer molding (RTM), pultrusion, and braiding.

This whole area must be pursued with the active involvement and participation of the machine builder. The machine company cannot be excluded from the process.

Qualification--The costs associated with qualifying new materials could be substantially reduced by using military specifications and more standardized tests. For example, the 3501-6 systems from Hercules has been qualified, requalified, and re-requalified by several companies and by different production programs within the same companies. Standard test methods and sharing of data could significantly affect this process.

Material Enhancements--One way to cut material cost is to use standard materials. The industry needs to get away from the current practice of having a large number of material systems going into a given production run.

New and improved product forms need to be developed. These include thermoplastic (TP) towpreg, TP broadgoods, RTM resins and preforms, and close-tolerance prepregs. These improved materials would allow for the use of low-cost manufacturing options. As noted above, one cost-reducing option available today is the sharing of materials data bases.

New resins are required for recommended low-cost processes to achieve their ultimate potential. Thermoset (TS) resins should be developed having controlled rheology that would allow them to be used in a "lay-up to full consolidation" process. A hot-head tape machine could be used to consolidate TS prepreg and to convert the resin to a cure-stage condition. This material would have excellent shelf stability and would be amenable to subsequent operations such as co-curing. A further cure would, of course, be required. Rapid cure resins having the performance characteristics of today's high-performance resin systems should be developed for those processes utilizing near-net-shape preforms, such as RTM or pultrusion. TP resins should be developed that have all of the attributes of today's resins but with a lower melt temperature and lower melt viscosity.

Quality Standards--A realistic quality data base will need to be developed for new automated processes. The quality standards will have to account for such issues as gaps, laps, voids, and porosity. This data base might be vital to allowing increased production rates during an emergency surge condition.

The development of in-process inspection devices and procedures coupled with the automated processes could have a dramatic effect on the cost-of-quality picture.

3. Recommended Programs

From this list of recommendations, the panel arrived at the following set of programs that address those recommendations that are within the scope of their charter:

- Materials placement
- Materials enhancement
- Design/manufacturing interaction (to a limited degree)
- Quality (to a limited degree).

These programs are shown on the attached roadmap (Fig. 4), with timing and program ties easily discernible. A brief description of each of the recommended programs follows.

High-Rate Lamination

Objective: To develop prototype machines and complementary close tolerance prepregs capable of significant reductions in processing costs.

Approach:

- *Prototype process/machine development*--Prototypes for high-rate lamination and full depth consolidation during lay-down will be developed.
- *Close tolerance prepregs*--Prepreg systems that will allow these processes to occur will be developed. Close tolerances will be required on such characteristics as thickness, width, resin content, and fiber content.
- *In-situ consolidation*--The ability to obtain complete consolidation (not necessarily full cure) during the lay-up step will be investigated.
- *Potential processes*--Hot-head tape machines, heated filament winding, fiber/tape placement, autocollation.
- *Quality*--Issues such as in-process inspection, quality control limits, and design interaction will be addressed.

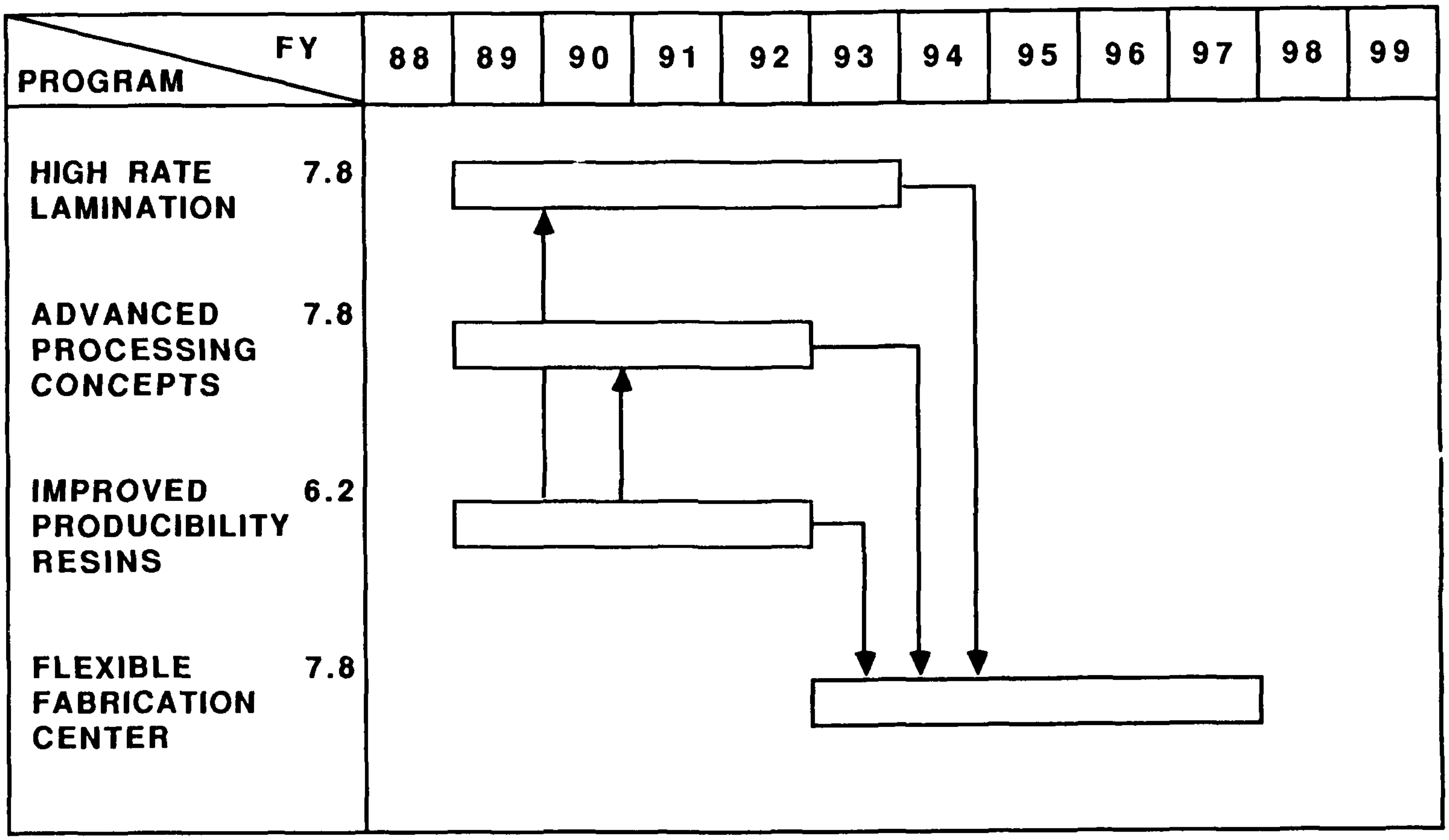

Figure 4. Materials and Processing Roadmap

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Payoff: Composite part fabrication steps beyond lay-up would be eliminated (with the exception of any further cure required for thermosets).

Advanced Processing Concepts

Objective: To develop unique product forms and associated processes that will allow significant reductions in the cost of composite processing.

Approach:

Unique product forms:

- Near-net-shape preforms will be developed. These are materials that have been pre-woven, pre-stitched, and pre-plied to approximately the shape of the final part by the supplier.
- Fully consolidated sheets/shapes will be developed. These are materials that have been pre-plied, pre-shaped, and fully densified by the supplier.
- TP broadgoods will be developed.
- Kitting would also be explored. This concept would entail the supplier providing pre-plied, pre-cut kits to the user. If these were relatively standardized, significant cost reductions could be realized.

Advanced Processes:

- Advanced processes to be developed and/or investigated include RTM, pultrusion, braiding.
- A cost/design demonstration would be a key feature of the program.
- Quality standards as described above would also be of prime importance.

Payoff: Could eliminate the lay-up and placement operations associated with today's production environments.

Improved Producibility Resins

Objective: To develop improved thermoset and thermoplastic resins that would provide those characteristics required of potential low-cost manufacturing processes.

Approach:

Thermosets: New resins would be developed that possess the following attributes:

- *Tailored cure rheology*--Rheology that would allow them to be hot-head tape laid such that they are brought to a C-stage state. In this condition the material would have very good shelf-life and still be amenable to subsequent operations such as co-curing.

- *Rapid cure*--This would apply specifically to RTM type processes, where resins that can cure rapidly and still maintain high use temperatures are required.

- *Low pressure cures*--This is specifically directed at today's processing regimes if a surge capability were required. Low pressure (e.g., vacuum bag) would allow processing outside of the autoclave.

Thermoplastics: New thermoplastic resins are required that will possess the following attributes:

- A low melt temperature, while maintaining today's materials' attributes.
- A low melt viscosity, while maintaining all of the attributes.

Payoff: Would provide both thermoset and thermoplastic materials which would allow for significant cost reductions during the composite manufacturing process.

Flexible Fabrication Center

Objective: To implement the advanced materials and processing concepts developed in the previous programs.

Approach:

- A factory floor analysis will be conducted to determine how these advanced concepts can best be integrated into the shop floor.
- Integration with existing software and development of new software will both likely be required.
- Special emphasis will be placed on the design/fabrication interaction.
- Several design/cost demonstrations will be performed.
- The shop floor analysis would include the capability to describe how these concepts would best fit a surge requirement.

Payoff: A totally integrated factory approach to manufacturing low cost composite hardware.

C. TOOLING PANEL

This panel was made up of a cross section of experienced composites engineering, manufacturing, and tooling specialists from military and commercial airframe and helicopter manufacturers.

The charter of the tooling session was stated as follows: Identify tooling technologies that will result in improved production efficiencies and reduced cost composite structures by 1995.

The panel session commenced, with selected presentations from the participants. These presentations served to identify tooling issues and problems relevant to particular segments of the industry. As the presentations continued, it became clear that many of the problems plaguing the companies are common, regardless of the type of aircraft or end user.

After these presentations, the panel was divided into three subgroups to identify common issues and propose solutions to the problems. The subgroups were:

Tool Design

Tooling Materials

Tool Fabrication/Assembly.

1. Background

Tools and tooling concepts for composite structures are evolving as experience is accumulated within the aerospace industry. Application of composites to aircraft has been primarily driven by weight savings intended to attain performance benefits. Now affordability, or lower initial cost and reduced life cycle costs, is becoming more important in an era of decreasing DoD budgets. This increasing emphasis on cost-effective composite structures is driving improvements in design and manufacturing technologies, with computer-aided design and manufacturing playing an increasingly important role.

While the design and manufacturing technologies are moving toward these cost goals, the tooling technologies have remained essentially static. Over the past 20 years, the tooling materials, design and fabrication technologies have received only minor shares of the development funds spent on composites. Tool designs and fabrication techniques are highly dependent on empirical methods, based on the tool designer's personal experience. This historical approach to tool design gives us a mismatch between the capabilities of the part design/manufacturing and tool design/fabrication process. Many cost-effective composite designs are grossly compromised by the inability of the tool designer to provide a compatible tool design.

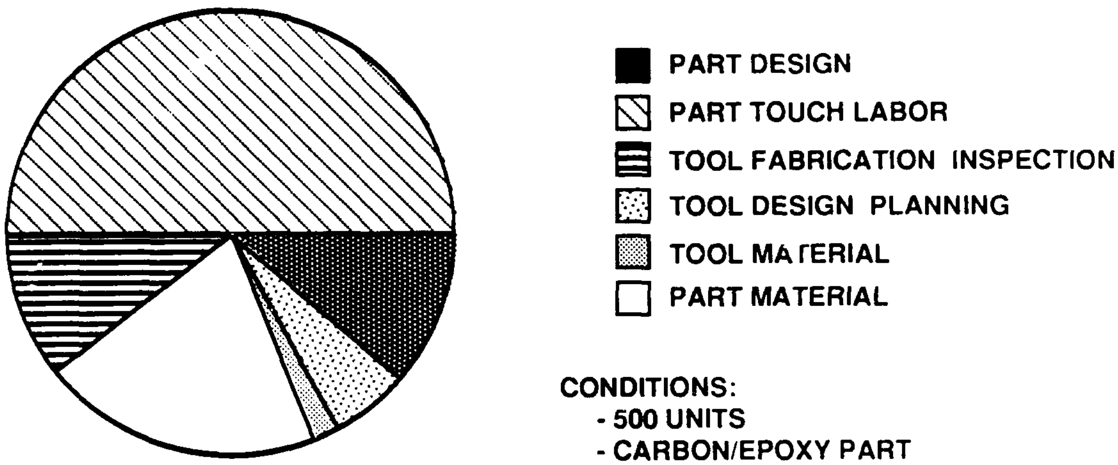
Tooling costs can have a significant impact on both nonrecurring and sustaining cost if the tooling is not perfect the first time. Many times tool development activities are conducted during the tool design/fabrication/verification cycle on a production program. This creates schedule delays, drives nonrecurring costs up, and can have an adverse impact on recurring costs because of compromised tool designs. Figure 5 illustrates the relative tooling costs as a function of total nonrecurring costs for a typical composite part. The tool costs will typically account for 15-25 percent of the total nonrecurring cost of a composite part. Figure 6 shows a further breakdown of the tool nonrecurring cost. Elimination of tooling rework, design of lower cost tools, and especially design of easily used and maintained tools will significantly enhance our competitive position, and at the same time, provide reserve capability to meet future surge requirements.

2. Challenge of the Future

Advanced, high-performance composite materials coupled with ingenious designs and processes impose even more stringent demands on tool design. Tooling must be more precise, environmentally tolerant, adaptable, and process-flexible to produce high-quality, affordable air vehicle structures for the 1990s. The tooling system must be compatible with the manufacturing system to assure integration into the composite integrated factory of the future. Material, process, and tooling technologies must be developed to permit the design and manufacture of composite parts that meet the engineering and quality requirements of the composite triad, as illustrated in Fig. 7.

The need for R&D focus on the tooling segment of the triad is required to dramatically lower the nonrecurring and sustaining program costs. Automated, user friendly tool design systems are required to bring the tool design capability on a par with part design capability. The incorporation of advanced sensors into the tools, with realtime process control models, is required for integration with future computer integrated manufacturing (CIM) systems.

As indicated in Table 1, there are parallels between the technology needs for lower part cost and those for lower tooling costs. Many of the technologies developed to lower part cost can therefore be applied to lower tooling cost. The challenge then is to build upon this existing technology base in identifying and executing future development activities in tooling, towards attainment of the truly cost effective composite structures on future weapon systems.



CONDITIONS:
- 500 UNITS
- CARBON/EPOXY PART
- ALUMINUM TOOLS

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Figure 5. Composite Part Cost

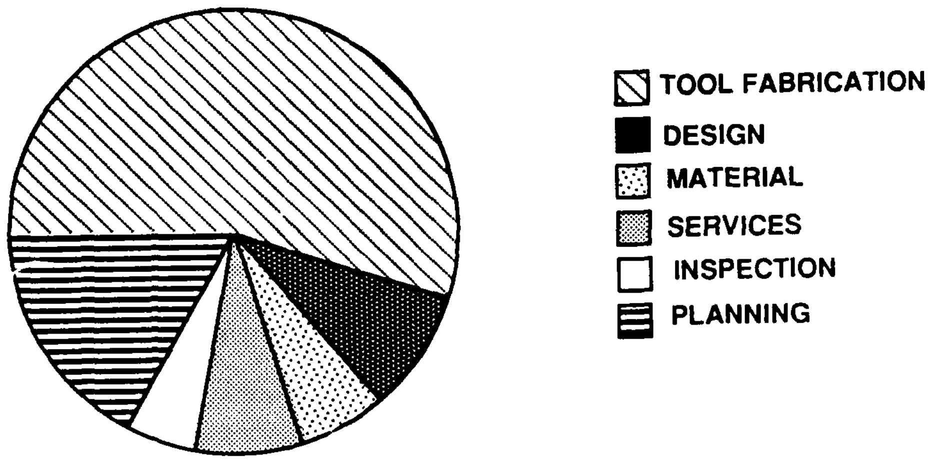

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Figure 6. Nonrecurring Tool Cost

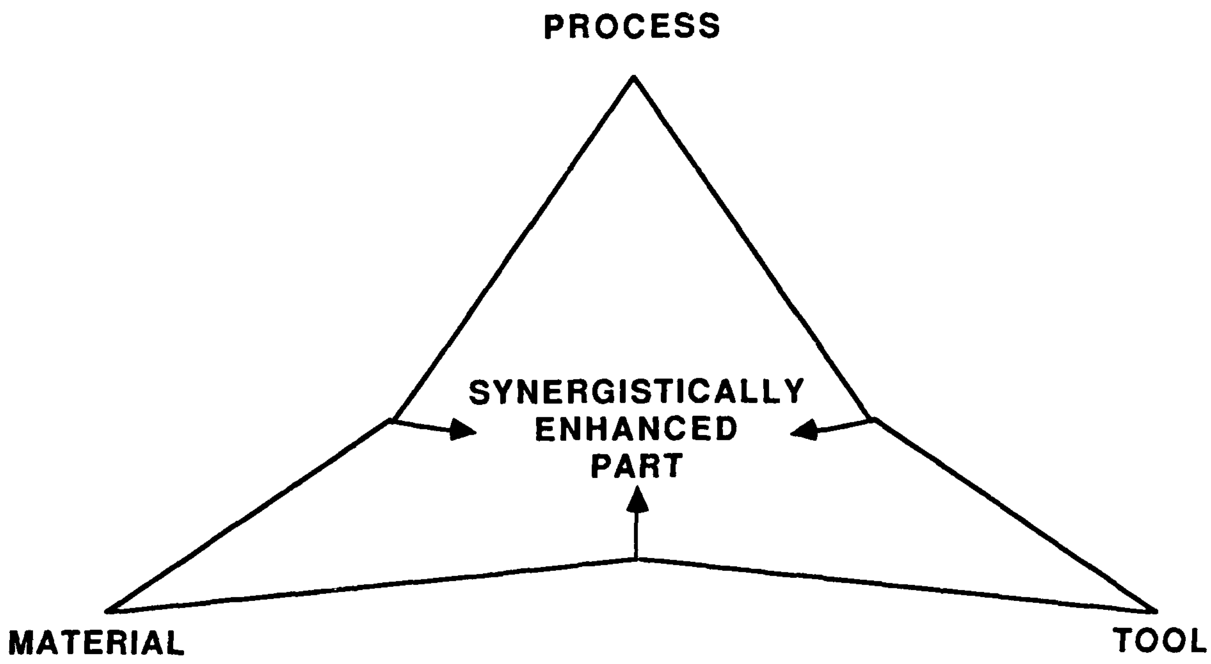

Figure 7. Quality Triad for Composite Structures

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Table 1. Cost Drivers for Composites

Part Cost	Tool Cost
Design Innovation	Tool Design Innovation
Design/Analysis Automation	Tool Design/Analysis Automation
Established Data Base	Established Data Base
Low-Cost Materials	Low-Cost Tool Materials
Automation of Planning	Tool Planning Automation
Fabrication/Assembly Automation	Tool Fabrication/Assembly Automation
Automated In-Process Inspection	Automated Tool Inspection

3. Tool Design

The future composite factory coupled with advanced performance composite materials will require greatly enhanced tool design capability to achieve composite part costs comparable to metal structures. Requirements for tool design can be summarized in four design-driven categories:

1. Physical criteria, such as durability, temperature, and pressure resistance, and environmental and dimensional stability.

2. Mastering requirements, such as dimensional control and stability, ease of fabrication, storage and movement, and repairability.

3. Tool fabrication costs, schedules, and quality.

4. Requirements for integration into the CIM environment.

Evaluating and relating these requirements to today's state of the art in tool design leads to the recommendations for technology improvements in the following subsection.

Tool Design Technology Approach

The ability to improve the tooling technology and have an impact on major performance/cost/schedule shortfalls will require extensive up-front investment by government and industry. Leveraged areas selected for technology development are:

1. *Tooling Design and Analysis Systems*

   An automated tooling design capability, employing expert systems technology, is needed to simplify and shorten the tool design process, and to apply engineering design and analysis capabilities to tool design.

   The system must consider each component of tool design and fabrication as well as supplier-furnished items.

   The system must possess the capability to learn (expert systems) so that lessons learned can be easily integrated on a real time basis. The output of the system would be an integrated/optimized tool design, including tool and manufacturing plans. The system must also include the capability to assess the cost impact of engineering tolerance variations, as well as account for thermal and material tolerance variations.

   The final output for a near-term system could be in the form of expert advice to the tool designer. In the longer term, the tool design system must have the capability to produce tooling drawings, and to electronically hand off tool design data to the tool production/fabrication processes.

2. *Tooling Configurations and Structural Analysis Program*

   This initiative would produce a tool design assistant computer code. The user friendly code must be capable of analyses using part compensation factors, material thermal conductivity and expansion factors, etc. The code would perform structural and thermal analysis of the part/tool combination, operating from the same electronic data base as the part design.

   This program would be an integral element of the Tooling Design and Analysis System discussed under item 1.

3. *Establish and Automate Non-design Tools*

This initiative would develop standards for form block and other tools. The standards would be integrated into a code to assist the user in the generation of these tools, using a knowledge data base with expert systems technology to retrieve historical data as well as design information. Assistance would be provided for material selection, processing quality control, packaging, factory movement and control, as well as other processes.

4. *Innovative Concept Development*

This activity would address advanced processes and concentrate on the tooling knowledge aspects. This would include development of concepts for cocuring (or coconsolidating) complex parts (to reduce part count and cost) as well as concepts to eliminate transfer tools (tools to make tools).

5. *Thermal Analysis Program*

There is a need for a tool design computer code that will allow the analytical prediction of the tooling configuration at various temperatures in an autoclave/oven environment. In addition, the code must predict the thermal distribution within the part/tool during autoclave/oven tool processing. This code must also cover heat-up rate optimization as well as long-term thermal stability of the tool.

This program would be an integral element of the Tooling Design and Analysis System discussed under item 1.

6. *Material Selection Analysis Program*

This program would consist of a tooling materials data base and material selection criteria to aid the tool designer in the selection of tooling materials for composite parts. The code would permit the rapid assessment of overall tooling cost and performance (ease of use, maintenance, etc.) as a function of the tooling material.

This program would be an integral element of the Tooling Design and Analysis System discussed under item 1.

7. *Quality Standards*

Standards are needed for inspection and acceptance of tools for composites. Especially critical are composite tools, where standardized inspection means and controls are needed.

8. *Industry Integration and Validation*

The overall technology developments discussed in the preceding will require validation and integration into industry tooling design and fabrication systems. A concerted industry collaboration is required to validate the methodology, materials, and other tooling technologies for a wide range of applications.

4. Tooling Materials

Tooling materials can be generally categorized by use temperature (oven, press or autoclave use) into the following ranges:

- Room temperature to 350 °F cure
- 350 °F to 600 °F cure/consolidation
- 600 °F to 800 °F cure/consolidation.

Further, tools can be classified as:

- Single surface tools, shallow (less than 6" draw)
- Single surface tools, deep (over 6" draw)
- Matched tools.

Each of these tool types can be further subdivided into small (less than 4 ft^2), medium (4 to 30 ft^2), or large (over 30 ft^2).

The approach to define the technology needs for materials was to define the areas where tooling materials are available according to the above classifications. The data in Table 2 is a first cut at surveying the materials data available for the tool types and temperatures. Those areas where materials and data are not available are the areas in which to concentrate developmental funds for tooling materials. Certain conclusions that were drawn by the panel regarding the state of the materials for tooling technology. These conclusions are itemized below for the three temperature ranges of interest.

Below 350 °F Cure Tooling Materials. Materials are generally available to fabricate 350-400 °F cure parts. However, these materials are not necessarily optimized for low-cost manufacturing. Technology needs for this class of material include:

1. *New or Improved Lower Cost Materials*

Material and process improvements are needed to provide materials that are optimized for low manufacturing cost--both in the tool fabrication and part production processes. Specific performance requirements that must be addressed include:

Table 2. Tooling Materials Survey

Use Temperature (°F)	Single Surface						Matched		
	Shallow			Deep			Shallow/Deep		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
R.T.	X	X	X	X	X	X	X	X	X
350	X	X	Exists, but expensive	Exists, but expensive			Exists, but expensive		
600	Exists, but expensive (Steel)			Exists, but expensive (Steel)			Exists, but expensive (Steel)		
800	Exists, but expensive (Steel)			Exists, but expensive (Steel)			Exists, but expensive (Steel)		

- Thermal characteristics compatible with part (low CTE, thermal stability)
- Durability or damage resistance
- Repeatability
- Ease of repair
- Ease of fabrication
- Machinable deep draw material
- Ease of machining, if required.

2. *Standardized Design Data*

Standardized design and processing data for tooling materials would provide significant benefits toward reducing tooling design cost, reducing schedule spans, and eliminating overly conservative tool designs. Most tool designs rely on vendor data or simple estimates ofthe material properties, resulting in errors in fabrication and processing that take time and cost money to correct.

3. *Eliminate Transfer Processes*

The traditional approach toward design of "plastic" tools for oven or autoclave cure involves the fabrication of a plaster master model followed by construction of a transfer plaster mold with the reverse image. The next step involves taking a fiberglass or plaster mold off the transfer plaster. This fiberglass mold then becomes the mold for the final fiberglass or graphite/epoxy tool. This multiple-step tool fabrication process is both time consuming and expensive. It also produces tools of limited life if room temperature cure two-part epoxy systems are used. Direct CAD-to-tool approaches[5] are needed to minimize the tool transfer process, and to eliminate the need for "tools to build tools". These approaches must tie into the CIM system of the future composites factory.

4. *New or Improved Lower Cost Secondary Materials*

   Improvements are required for sealants, bagging materials, and mandrel materials to provide both lower cost and higher temperature capability. Sealant and bagging materials are extremely high-cost items in the cure/consolidation process. The inclusion of these items in the overhead charge rather than in the direct rate charge tends to mask or minimize the cost impact in most instances--but we must significantly reduce these costs if we are to attain cost-effective composite structures.

350 °F to 800 °F Tooling Materials. The requirements for high-temperature tooling materials are the same as for the lower temperatures, with the addition of the following:

1. *Practical Alternatives To Steel Are Needed*

   Most high-temperature tools are fabricated from steel because of its stability, strength, and ease of machining. Current alternatives consist of ceramic, bulk graphite or prepreg graphite materials. The first two are brittle and need special handling to prevent breakage. The prepreg tools require expensive transfer tools to fabricate.

   There is a need for low-cost tooling materials that can be laid up directly onto a master model, cured at room or low temperature, and post cured at high temperature to attain the required strength and durability properties.

2. *Pressure Media For Complex Shapes*

   The means of applying pressure for high temperature cure processes require improvement in properties as well as reductions in cost. Films (bagging materials), bladders, mandrels, and caul plates are limited in life or performance at the elevated temperatures required for thermoplastic or polyimide materials, as well as being extremely expensive.

   At the higher temperatures, such as required for thermoplastics and polyimides, bagging and sealing materials become a problem. Sealing of the bag often requires double bagging to prevent burn-through. High-temperature

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[5] CAD = Computer-aided design.

bagging materials are extremely expensive and come in limited widths, requiring seam welding for wide parts.

5. Tool Fabrication and Assembly

Tool fabrication and assembly technology improvements are required to achieve cost reductions in tooling and to meet surge capabilities. Automation of the tool fabrication process offers little payoff because of the limited numbers of tools to be fabricated of a given configuration. Rather, other technology improvements are needed to provide improvements in data flow to the shop, in estimating the cost of tools, etc., as delineated below:

1. *Standardized Skill Ratings*

Standardized skill ratings are needed to simplify the transfer of personnel and data between aerospace companies.

2. *Develop Technology to Replace High Skill Levels*

Technology developments are needed to replace the high skill levels currently required to fabricate composite goals. Better and more easily used materials and processes will go a long way toward reductions in skill levels and eventual lowering of tooling costs and shortening of schedules.

The same is true for inspection of composite tools. The current need for highly qualified tool inspectors must be reduced through the development of technology for automated inspection.

3. *Shop Access to Computer Design Software*

Computer software is needed to link the tool fabrication shop to the tool design data base, to provide instant access to the design data for resolving problems as they arise in the shop. This software could tie directly into the CAD data base, but would not provide the capability for changes in the data base.

4. *Accurate Estimating Standards*

Accurate estimating standards for tool fabrication and maintenance are needed to eliminate uncertainties and reduce conservatism in quoting composite tools for production programs. There is little historical data on which to base estimates, and with a lack of design methods, many quotes for composite tools are sufficiently high to prevent initiation of the program.

Pooling of industry data, especially from DoD-funded production programs and R&D programs, would provide a basis for initiation of estimating standards for composite tools.

5. *Military Specification for Tool Coding*

Tool codes for composite tooling vary between companies (and often between different companies within a corporation), creating confusion and potential errors when transferring tooling data or tools between companies. The industry today is highly dependent upon subcontracting of tool design/fabrication, and a Military Specification for tool coding is needed to provide standardization.

6. *Improved Tool Designs*

Improved tool design concepts are needed to minimize loose tool details, thereby reducing tool cleanup, handling, storage, and maintenance requirements. In many cases, the use of composite tools, with thermal coefficients matching that of the part, will significantly reduce the need for loose details. However, the design methods to achieve highly complex composite tools are lacking, as noted previously in the tool design subsection. Improved tool design concepts, with the companion tool design methodology, will result in reduced tool recurring costs as well as reduced part fabrication costs.

6. Automated Electronic Composite Design Meeting Tool Design Guide

There is a need for an automated electronic data base to include all historical data relating to composite design, analysis, planning, tool design, tool fabrication, and part fabrication data. A major problem with any new technology is technology transfer, and one of the inhibiting factors in the application of composites technology has been the problem of getting the design/manufacturing technology from the development community into the hands of the production design and manufacturing specialists. There is a related issue in the lack of transfer of lessons learned on production programs into the next production program--even within the same company. We find that in many instances, the same mistakes are repeated on each sequential program because of the lack of a suitable technology transfer mechanism.

The incorporation of the historical data base into an electronic data base will made the data easily accessible to the design/manufacturing specialists. Today's computerized publishing systems, coupled with expert systems technology, provides the capability for quick access to vast quantities of data. Memory and data storage devices are low in price, making it feasible to provide each specialist with a terminal with which to access the data base.

7. Roadmaps

The roadmap shown in Fig. 6 illustrates the tooling programs recommended by the Tooling Panel. There are two government technology programs planned relating to the subject of cost-effective composite structures:

Tooling for Composites	AFWAL/ML
Advanced Concepts and Materials	NASA/LaRC

The Air Force's Manufacturing Technology Division is currently planning an FY 89 program called "Advanced Tooling Manufacture for Composite Structures." The purpose of this program will be to establish and validate an integrated methodology for tool concepts, selection, and design functions for the manufacture of improved tools for production of composite structural components. Emphasis will be placed on the use of current manufacturing technologies and practices for tool manufacture and information management and process modeling to establish and validate an expert system capable of assimilating tool modeling, materials, and analysis information into a knowledge-based advisor system for presentation of tooling options and tradeoffs relative to part quality, tool durability, and lower cost/cycle times.

These planned programs need to be supplemented with additional development activities directed specifically at tools for fabrication of composite structures. These proposed programs are noted in Fig. 8, and would build upon the technology developed in the planned Materials Laboratory tooling program. Briefly, these proposed programs would cover:

1. **Design**--This program would cover the tool design issues addressed in the design subsection, as well as some of the issues addressed in the tool fabrication subsection. Specific issues would include:
   - Tool design/analysis methodology and automation of the methodology into an automated tool design system. This system would build upon the design system planned in the FY 89 Materials Laboratory program.
   - Tooling concept and configuration development.
   - Development of non-design tools (form blocks, etc.)
   - Collection and incorporation of existing tool design data into an automated data base.

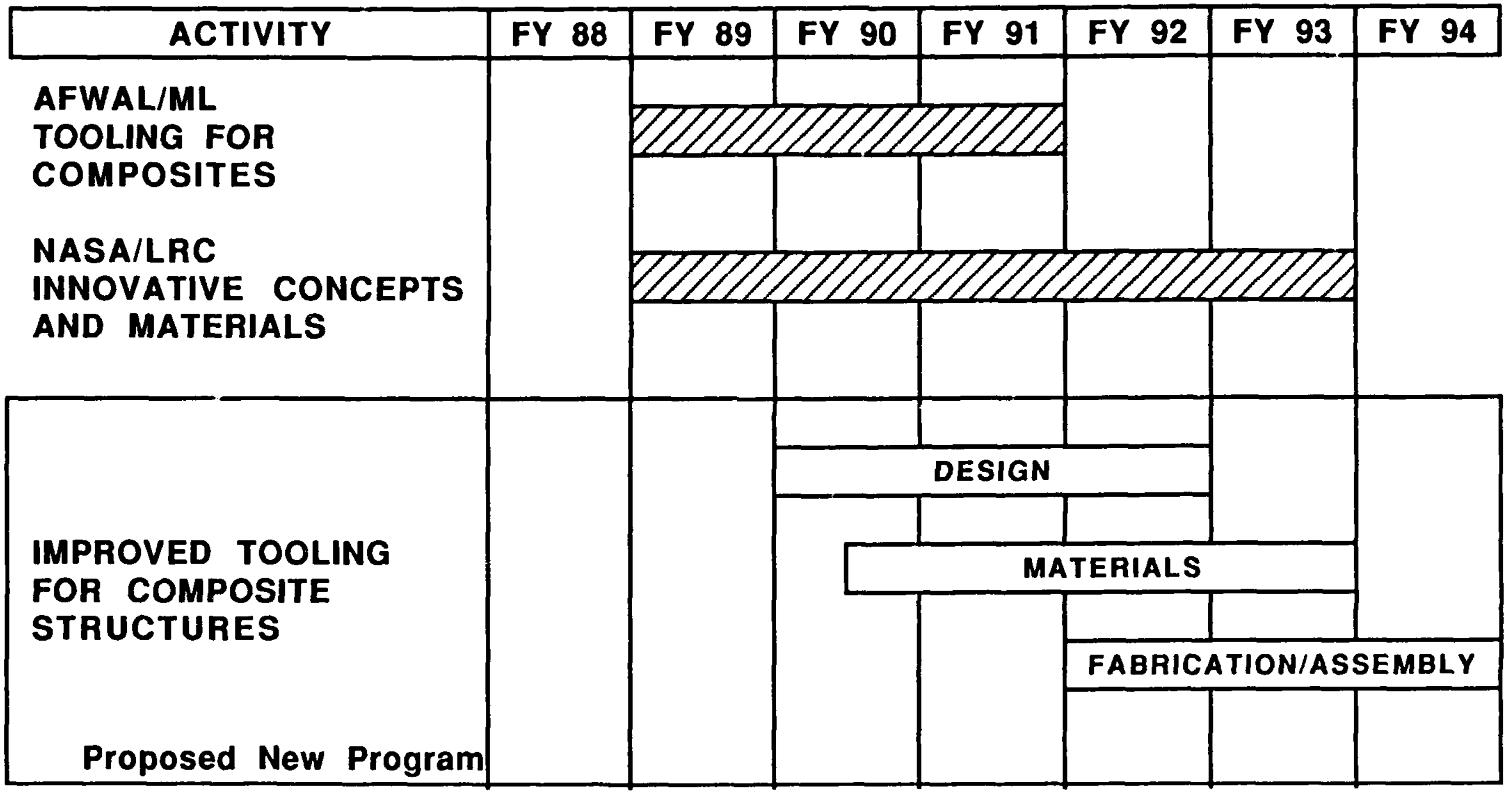

Figure 8. Tooling Roadmap

WH:kg-8
3/21/89

2. *Tooling Materials*--This program will cover the development of improved tooling materials, oriented toward low cost and ease of fabrication. The temperature ranges include room temperature to 800 °F. In addition, the characterization of existing and new tooling materials would be included, with all data being incorporated into an automated data base available to industry and government.

3. *Fabrication/Assembly Automation*--This program will develop standard hardware and develop methods for automation of the fabrication and assembly steps for composite tools. This effort will address standardization of skill ratings for composite tool workers as well as development of tool coding standards.

D. LAYUP AND ASSEMBLY PANEL

1. Introduction

New aircraft systems, which are planned for production initiatives in the 1990s, i.e., ATF, LHX, V-22, etc., will utilize advanced composite material systems to achieve improvements in operational performance, cost, and weight characteristics. Fixed Wing and Rotary Aircraft industry manufacturing personnel were brought together to identify composite material manufacturing and assembly issues and limitations which need to be resolved if future production rates, affordability limits, and surge capabilities are to be achieved. Our current composites production manufacturing base is greatly dependent upon hand layup and consolidation of composite materials, secondary bonding operations, use of limited material forms and high turnaround times of equipment/tooling/facilities. Each of these factors substantially inhibit production efficiency. Industry workshop panel members were requested to present a Government-sponsored project considered most needed to lower the cost of composites in the category of material layup and assembly. During project presentation the discussion was focused on identifying specific task/initiatives in the areas of manufacturing methods and equipment for handling composite materials throughout their fabrication cycle. The projects focused on a number of manufacturing approaches, and in many cases, identified candidate end item demonstration articles. Key manufacturing technology thrusts included: "Mechanization of Multi-Ply Composite Fitting," "Automating the Fabrication of Advanced Composite Structures," "Maximizing the Efficiency of Manual Layup of Composites," "Automated Thermoplastic Material Handling and Assembly," "Redesign Transfer Molding (RTM) of Monolithic Three Dimensional Structures," and "Manufacturing Technology for Large

Aircraft Primary Structural Wing." Improved operational performance and reduced cost and weight can be demonstrated and substantiated through the initiation and implementation of these and other Man Tech initiatives.

2. Background and Current Status

DoD has determined that industrial readiness and capacity for the application of advanced composite materials for new aircraft systems in the 1990s will not occur in time unless pacing issues are identified and production solutions initiated. Anticipated production rates in the 1990s require development of automated manufacturing methods to provide affordable and producible advanced composite airframe primary structures. The opportunity to expand our current composites manufacturing base (which is largely dependent upon manual layup processes, secondary bonding operations, and use of limited material forms), must be undertaken in a timely manner to avoid excessive risk and potential limitations on cost/weight and performance goals of future aircraft programs.

Pacing issues and manufacturing technology areas which were identified include the following:

- Advanced tape layup equipment for larger and more complex contoured aircraft structural components.
- Structural component layup with integral reinforcement, 3-D preform, and resin transfer injection/press molding techniques.
- Automated flat material dispensing, cutting, pickup, kitting, and delivery to fabrication site.
- Direct efficient support of "hand-labor intense" fabrication processes and techniques.
- Improved autoclave curing techniques.
- Availability of improved thermoplastic materials forms
  --Woven prepregs
  --Broadgoods 45° to 90°, seamed.
  --Preplied/preconsolidated broadgoods
- Improved thermoplastic material characteristics, i.e., tack, conformability, warpage.
- Establish and implement an automated process control center for composites as technically and economically feasible, with emphasis on in-process defect detection.

- Improved equipment and material interfaces for thermoplastic layup.
- Flexible manufacturing cells by modular/interchangeable design of material dispersing equipment, tooling, and standardization of shapes and sizes of structural elements.

The development and demonstration of these manufacturing areas for highly complex/contour components is considered essential to achieving high payoffs of weight, cost, and performance for primary aircraft structures. Without risk reducing manufacturing technology demonstration projects, future development/production programs could be severely jeopardized by cost overruns and schedule slippage, or result in aircraft systems that will not exploit the real benefits and potential of composite airframe structures.

3. Summary of Panel Session Results

The specific projects and areas of needs that were identified by the workshop participants are as follows:

a. Manufacturing Techniques for Large Aircraft Primary Structural Wing (Rockwell International)

With the successful completion of advanced R&D and ManTech programs, the demonstration of manufacturing technology for production of large-aircraft composite wing structures has been significantly advanced. A number of existing materials, material forms, curing procedures for ultra-thick laminates, and innovative tooling concepts and equipment have been brought to a higher level of capability. However, these accomplishments were limited, based on the use of existing state-of-the-art materials and advancement of existing processes and tooling technology.

Consequently, a high payoff manufacturing technology effort needs to be initiated and directed toward extending the limits of capability of current processes and technology. Equally important is the use of advanced materials and materials forms, namely thermoplastic, which has the potential for significant reductions in labor/equipment processing times, and attendant improved structural durability. Specific areas of advanced manufacturing technology which are recommended include:

1. Further development of tape-laying techniques to provide the capability for automatically producing compacted, net end cuts on oblique tape courses to match the angled edge of the part (sensor recognition) of a ply dropoff station (preprogrammed).

2. Further development of six-axis fiber placement techniques to provide the capability to fabricate sections more complex than simple channel with straight taper; e.g., airfoil contour ribs with skin flanges.

3. Further development of breakdown mandrels for six-axis fiber placement methods to allow fabrication of closed structure; e.g., close box section longerons.

4. Development of fiber/thermoplastic fabric materials with appropriate techniques and/or heated tooling for producing laminates on compound curved surfaces.

5. Further development of fiber form, resin infusion, and pressure molding techniques to provide the capability for producing composite replacements for complex casting and forging shapes. (Substitute parts can be made now by chopped-fiber molding, but the preshaped fiber form design would be significantly stronger.)

The proposed approach would be directed toward fabrication of a full-scale B-1 wing section with integral stiffened skins and single-cure processing. Weaving of 3-D preforms (including weaving, impregnation, and curing) for longerons and ribs, improved tape layup techniques to form complex aerodynamic skin shapes, and the use of advanced thermoplastic materials would constitute the main areas requiring manufacturing demonstration. The emphasis on integral structural concepts is essential to reducing parts counts, joints and costs of assembly.

There are currently a number of material and equipment limitations that must be addressed in order to fully meet project goals. They include the following:

1. Thermoplastic layups beyond the size limits of 3 ft by 3 ft and 14 ply thickness exhibit unacceptable material warping and curl-up in the uncurved stage.

2. Fiber/thermoplastic impregnation material forms are quite limited.

3. Current weaving equipment is limited to parts 10 ft in length, while the capability to handle parts up to 49 ft long is needed.

b. Automating the Fabrication of Advanced Composite Structures (Lockheed Aeronautical Systems Co.)

The emphasis in advanced composite structures is moving away from demonstrating composite material acceptability toward developing cost-effective manufacturing methods. Machines capable of depositing advanced composite tape material in flat and moderate contours are now commercially available. While these machines do meet some of the need for automation of composite material deposition; co-curing of complete structural assemblies, reduction in part count, and reduction in labor-intensive assembly operations are not being sufficiently addressed. Prototype multi-axis and multi-system tape/tooling machines have been developed at Lockheed to demonstrate fabrication of composite structures with integral "3D" stiffners in the size ranges of 48 in. in diameter or flat structures 10 ft by 4.5 ft. Several interchangeable material deposition modules for the basic tape machine have also been developed. The different thermoset/epoxy material forms include (1) 3-in.-wide preimpregnated unidirectional tape, (2) 1/4-in. and 3/16-in.-wide syntactic coated preimpregnated carbon/epoxy tape, and (3) dry fiber/wet resin, or preimpregnated tow (filament winding). The initial feasibility/equipment development program has shown that a variety of flat structural configurations and three-dimensional geometric shapes can be fabricated. However, configuration issues and machine flexibility for full-scale aircraft structures (i.e., tapered configurations, complex contoured surfaces, and varying configuration requirements of integral stiffeners) limit the direct application of this manufacturing technology into production structural components.

Accordingly, the design and full-scale fabrication of complex, integrally stiffened structures of actual aircraft components for risk reduction development/demonstration is needed. Candidate structural components include fuselage structures with frames, ribs, and skins and wing sections with ribs, spars, and skins. Accompanying technology improvements which must also be demonstrated include proper tool design to control uncured composite details and section during their combined curing/assembly operations. The need for advanced manufacturing processes and innovative tool designs that facilitate cost-effective fabrication of multi-element composite structures is clear. Efforts must be continued toward development of methodologies which can be integrated and implemented into current production processes for utilization in the 1990s in support of new aircraft programs.

c. Mechanization of Multi-Ply Composite Fittings (Bell Helicopter/ Textron)

In the course of composite program reviews and technical presentations, the emphasis has primarily been focused on large composite structural components, i.e., wings, fuselage sections, and selective secondary airframe components. These components offer the potential for significant improvement in cost, weight, and structural performance. However, application of composite designs and manufacturing processes for smaller structural components such as joints, fittings, and attachments can provide substantial gains for flight-critical components. These composite components are applicable to both fixed-wing and rotary-wing aircraft and include applications for landing gear fittings, empennage attachment fittings and rotor system "grip" attachment for the Tilt Rotor V-22 aircraft. The application of composite designs to replace conventional metallic fittings provides reduced weight, improved cost, and extended operational life as a result of inherent composite material durability properties.

The latter or final stages of fabrication and assembly of selected, small composite components are generally well suited to current state-of-the-art automated and semi-automated filament winding and tape layup manufacturing processes. Additionally, tooling requirements are fairly well defined and collectively provide good cost reduction as compared to metallic counterparts. However, efficient ply management of detailed critical structural elements of multi-ply composite components, i.e., ply build-up/filler packs, load straps/belts, mandrel wraps, and fittings has not kept pace with other manufacturing processes. The material layup, cutting, stacking, kitting, and transfer of the uncured structural elements to the user site continues to be a highly labor-intensive operation that substantially affects the cost of the final component.

The approaches and benefits are identified as follows:

- Large multi-ply components present formidable hurdles to ply management systems from two perspectives. First, by their large ply count they increase the involvement of information management which adds cost but no value to the end article. Second, large quantities of plies dedicated to single parts require extraordinary provisions for sorting, staging, and moving.
- In order to minimize this impact on component cost, super efficient methods must be in place that provide alternatives to current labor-bound operations.
- The feasibility and benefits of combining selected technologies to create a ply management station capable of mechanically preparing complete ply kits for multi-ply components will be established.
- The sorting and kitting station receives plies randomly from preparation sources. Optical "readers" would be utilized to automatically identify each ply in terms of specific part and kit requirements. Mechanical effectors would then pick and sort accordingly. After arranging the plies in correct layup sequence, the transport system would be activated to deliver the individual kit(s) to the user station.

The V-22 rotor grip was selected as the best and most complex fitting assembly to demonstrate an automated multi-ply kit assembly. Assuming a 102 aircraft requirement for 1988, the station would process more than a million plies for this item during that year.

Accordingly, considerable time, cost, and material scrappage reductions with improved quality of the fabricated end item needs to be accomplished.

Manufacturing steps and assembly sequences proposed for the fabrication of a Tilt-Rotor V-22 composite group are as follows:

- Filament winding of belts
- Locate compression-molded blocks on mandrel
- Helically wind torque wraps and split transverse
- Locate belts and hot drape form filler packs on assembly
- Vacuum compact
- Insert bag for internal pressure
- Autoclave cure.

d. Maximizing the Efficiency of Manual Layup of Composites (Boeing Helicopter)

In the manufacturing of composite components, extensive use of hands-on, labor-intensive operations are part of the current fabrication process. It is recognized that a number of these manual processes can be replaced with automated/mechanized processes that can accomplish these same functions quite well and more efficiently than manual approaches. However, it must also be recognized that manual manufacturing processes will still be required in the future where they provide the best or only approach. Simply stated: let machines do what they do best and provide the technical/equipment support to make required manual "hands-on" processes the most efficient and practical solution.

The limitations of automated composite material layup and mechanization of associated manufacturing processes deal mainly with the following conditions:

- Automated tape layup machines have been designed for and provide the best support of large wing and fuselage skin panels.
- Composite layup of highly compounded, tapered, complex contours typical of Helicopter/Tilt Rotor fuselage skins and frame structures are generally not compatible with current equipment capability, i.e., tape head compliance to slopes and build-ups is limited.
- The tape and filament layup of conical/curved shapes, with high contour and/or tapper, significantly reduce material deposition rates due to the need for complementary fiber drop-off and area build-up processes. These complementary processes/functions for the most part will involve hands-on

assistance and are necessary because both tapes and filaments must be laid in a natural path. This natural path layup can also restrict the fiber angle achievable during automated layup, thus requiring additional plies (increased cost and weight) to obtain desired structural properties of the component.

- Current in-process controller, inspection, and fault detectors are limited in their capabilities and cannot respond with immediate corrections.

In order to maximize the effectiveness of human dexterity, the specific tasks which will require human processing must be recognized and automated support functions defined. A listing of support functions that would enhance composite layup and assembly is as follows:

- The largest impact on reduction of cost, time, and improved quality of manually laid-up components can be achieved by the development of a dedicated process cell. This cell would be responsible for cutting, marking/pickup, kitting, and eventual trimming of structural elements. These automated preformed elements would then be integrated manually into the component layup and assembly operation.
- Utilizing automated equipment to provide composite materials in needed forms to the manual layup suite. This will require more extensive use and development of braided, woven, and stacked broadgoods to provide cured/uncured composite materials in the form needed.
- Improved shimming and use of no-bleed compliant tooling for thickness control has been incorporated into the Tilt Rotor V-22 development program. However, substantial improvements in these methods and development of more innovative approaches to improved component fit and eventual assembly is needed. These assembly processes must focus on both adhesive bonding and optimum use of mechanical fasteners.

e. Improved Autoclave Curing Techniques (McDonnell Douglas Helicopter Co.)

Current autoclave processing utilizes batch loading, thermal maps, and process modeling to characterize resin systems during the curing cycle. Real time feedback controls on both parts and tooling have enhanced quality. However, autoclave processing costs need to be reduced further and provide more flexibility to support surge capability. The primary goals of improved autoclave curing are as follows:

- Reduce curing times from a nominal 12 hrs to 4 hrs.
- Improve in and out times of tooling.

- Provide repeatable/secondary bonding process capability to support section repairs and element/component build up of complex multi-element components.

One of the most promising approaches to improved autoclave curing is the use of integrally heated tooling. Generally, autoclave heat-up and cool-down rates are driven by equipment/mass constraints and not materials processing/property limitations. Both air and liquid media circulated through the tool during pre- and post-cure cycles offers potential for reduced curing times. Additionally, during the curing cycle the presoak, gel, curing, and post-cure functions can be better controlled for individual components within the batch-loaded autoclave to provide part quality. During component fabrication, it is often necessary for a structural component to be returned to the autoclave a second or third time for repair of defective area(s) closed by vacuum bag breakage, part slippage, etc. Additionally, many complex, high-parts-count components require multi-staged element build-up to form the complete component. Each of these manufacturing processes can be substantially enhanced by integrally heated tooling. It should be noted that for large composite components an autoclave 350°C cure capability provides the best structural integrity. The use of heated tooling is generally limited to 250°F curing; therefore, the tooling process must be supplemented to achieve optimum material properties of epoxy material systems.

f. Resin Transfer Molding and Preforming Large Complex Structures (Sikorsky Aircraft)

Most conventional roof design alternatives require a large number of metallic clips, angles, truss members, and fasteners, along with expenditures for subsequent mechanical assembly to meet interior reinforcement requirements dictated by airframe designers.

A potentially improved design and manufacturing approach could be based on the application of resin transfer molding techniques (RTM) to produce large, co-cured "eggcrate" sections for a helicopter roof under-structure. This understructure would consist of an integrally molded grid work of spars, ribs and caps. Pre-cured skin panel subassemblies could next be bonded to the grid work understructure to complete the roof fabrication task. Such an approach could substantially reduce the number of fasteners and fixtures for bonding and assembly. It could also significantly reduce structural weight.

The resin transfer molding approach for the roof under-structure would produce several "waffle type" area sections which would then interlock with adjacent waffle sections to form a stiff, nearly monolithic reinforced structure. The RTM process would produce an accurate structure with integrally molded wall variations, steps, and reinforcements as a direct product of the mold. The "waffle" matrix, once assembled, would be ready for bonding/fastening on upper and lower skins.

In addition to demonstrating the feasibility of this innovative RTM design, it would be practical to demonstrate an equally innovative tooling concept. This concept combines a steel, "waffle iron" type upper mold with a mating steel or thermoplastic "waffle iron" type lower mold half to accomplish the resin transfer molding process. In operation, the rigid, thermoplastic lower mold half would be pressurized during both the resin injection and curing cycles. The lower mold half simultaneously serves as a carrier for dry, component preforms and as a debulking medium during the cure cycle to achieve higher fiber-to-resin ratios.

The application of the RTM process to the manufacture of primary structures the size of a helicopter roof section would be a substantial undertaking. The development and evaluation of this new approach would be a good candidate program to significantly expand the current composites manufacturing technology development base.

g. Process Control for Composites (PCC) (LTV)

The objective of the proposed project is to enhance the sensory, analytical/decision-making and control capabilities of human operators and replace these where humans are not within the control logic path. A complementary and equally important purpose is to reduce raw material testing and end-item inspection. Throughout design, development, and implementation stages, the process control function needs to be emphasized in order to achieve higher percentages of raw material as delivered components.

With primary focus on composite-laminates production, steps are needed to minimize the frequent labor-intensive, error-prone inspections used to verify ply location/ orientation and to identify anomalies, through implementation of process-control-driven automated tape laying machines and in-process vision systems. Autoclave curing processes also can be optimized, thereby reducing scrap and rework, by applying process control which accommodates both conventional monitoring devices and more advanced adaptive cure monitoring systems. Ultimately, a comprehensive, closed-loop process control system will reduce final inspections and tests of all manufacturing processes. Through the development and implementation of a database management system comprised of performance data from dimensional, ultrasonic, and coordinate measuring machine inspections and laboratory tests, expanded process control for composites can be initiated.

A four-stage project needs to be executed according to proven systems engineering techniques as identified under appropriate ICAM Project(s), "Factory of the Future." Stage I would include the determination of the causes of product nonconformance in composites manufacturing and functional specifications for a process control system. In Stage II, a process-tailored, real-time, closed loop, AI-based analysis and control system would be designed. Stage III would accomplish the development, testing, and demonstration of the system in an advanced flexible composites fabrication center. Finally, the system would require validation as technically and economically feasible during Stage IV.

The maturity of improved composite manufacturing technologies and a multi-disciplinary understanding of them should ensure the successful implementation of real-time, reliable process control on future aircraft systems. The proposed project will involve practical, manageable, low-risk development of critical enabling technologies, and implementation tasks for timely technology transfer to suppliers, customers, and the balance of industry.

4. Conclusions and Recommendations

- "Mechanization of Multi-Ply Composite Fittings" was selected as the most notable project presented. The combined attributes of ply management of kitted materials with fiber winding placement and control provides a unique approach to the fabrication of high-density, thick laminates, with substantial reductions in weight as compared to metallic parts.
- "Maximizing the Efficiency of Manual Lay Up of Composite" provided a project approach which was readily identified as an area requiring special consideration and need for focused effort. The use of manual layup for highly compounded contoured parts will be required to extent for both current and future programs. In order to minimize the labor-intensive operations of ply layup, automated cutting, kitting, in-process ply location marking, and inspection must be improved and readily available at user station(s). This manual fabrication approach can be further enhanced by extending the application of broadgoods material forms.
- "Automating the Fabrication of Advanced Composite Structures" is the key to cost reduction and component reliability/repeatability. A modular manufacturing system with the flexibility to fabricate a variety of structural configurations is an essential part. Such a manufacturing system should be

capable of producing integrally stiffened geodesic "3D" structures. An orderly transition from thermoset to thermoplastic material forms with innovative tooling concepts are important considerations if the total requirements for composite fabrication are to be achieved.

- "Thermoplastic Tape Lay Up" was identified as a manufacturing process for which unique material forms, process support, and innovative dispersement techniques and significant equipment development was needed. Automated layup machine builders and material suppliers must take the lead to develop practical, affordable equipment and material forms.

III. WORKSHOP FINDINGS AND CONCLUSIONS

A. SYSTEM PERFORMANCE HAS BEEN THE PRIMARY CONCERN IN COMPOSITES APPLICATIONS

Since the properties of composites became known and accepted throughout industry and Government, the emphasis has been on improved system performance in military hardware. The weight savings offered by composites provided a strong incentive to increase payloads or extend the range in weapon systems. During this period, the important considerations of producibility, maintainability, and affordability were essentially bypassed. Now that composites have proven their worth in systems, attention needs to be focused on the other factors which will determine the long-range acceptance of composites.

B. DESIGN APPROACHES WITH COMPOSITES HAVE BEEN CONSERVATIVE

It is generally conceded that the design of composite structures has been hampered by following the design philosophy associated with metal structures, whose properties are more nearly isotropic. Full advantage has not been taken of the benefits derived from the use of composites. Also, advances in materials development have not been utilized to their fullest extent because of restrictions in systems development programs to minimize risk by using only state-of-the-art materials. For the same reason, new materials developments are not provided the opportunity to prove themselves because the development period for demonstration is not compatible with the system development and production schedule. Automation has not been a primary driving force because production rates in the past have been relatively low.

There are uncertainties about the effects of defects in composite structures which tend to force designers to be conservative. Tolerances on dimensions and defects are generally considered to be unrealistic.

C. COMPOSITES DESIGN DATA ARE LIMITED

As a result of the continual development of new composite materials, very few materials have reached the level of consistency and reproducibility required for quality high-rate production. Furthermore, the consumers (systems development organizations) generate design data on a specific material for a specific application and tend to retain the data as proprietary information. Pooling of data from various sources is seldom satisfactory because of differences in material form and testing methods. This situation is particularly prevalent among the thermosetting resin systems. Design data on the recently developed thermoplastic resin composites is practically nonexistent.

D. COMPONENT DEVELOPMENT CANNOT BE CONDUCTED IN PRODUCTION

Experience has demonstrated that attempts to develop composite components as part of a production program are not satisfactory. The production schedules do not allow sufficient time for proper development with minimum risk. Yet, development must be undertaken on high-risk materials in order to make advancements in weapon systems capability. In order to provide the proper environment for development, the component development should be related to but decoupled from the production program.

E. MANUFACTURING EQUIPMENT DEVELOPMENT NEEDED FOR HIGH-RATE PRODUCTION

Production equipment development is frequently associated with the production program without the benefit of prototype development, resulting in less than optimum production facilities. As in the case of component development, there is a need to allow time for equipment development prior to production. While universal equipment is desirable, special equipment will be required for some advanced materials. Demonstration of producibility is essential before putting newly developed equipment into production.

F. DOMESTIC SOURCES, STANDARDIZATION, AND COST REDUCTION OF MATERIALS IS NEEDED

As pointed out in previous studies, there is strong reliance on foreign sources for some materials involved in composites manufacture. While steps are being taken to reduce this dependence, there is a need for qualification of sources. Present qualification procedures involve separate qualification of a given material by each individual program, resulting in much unnecessary duplication and added cost.

Some degree of standardization of materials, test methods, qualification criteria, and product forms should reduce overall material costs and enhance producibility. Action is needed in all of these areas.

G. LABOR-INTENSIVE OPERATIONS REQUIRE PERSONNEL TRAINING

Many steps in the manufacturing of composites hardware are now performed manually but could be improved through automation. However, manual labor may be most efficient and practical for highly contoured components which do not lend themselves to automation. In these cases, automation of the preliminary steps, such as cutting and kitting, may be of great assistance in the subsequent manual operations, to ensure quality control and producibility. The dependence on manual labor creates the need for training of personnel. It is estimated that up to 10 yrs may be required to train a person adequately. At present, there are no standardized criteria for qualifying composites production workers, either for tooling manufacture or material handling.

H. INSPECTION AND QUALITY CONTROL CRITERIA ARE NOT WELL ESTABLISHED

There is still much manual labor involved in inspection and quality control, using techniques which require interpretation by individuals. For high-rate production, emphasis is needed on the development of in-process inspection techniques and acceptance criteria to reduce the human element.

I. TOOLING MATERIALS AND CONCEPTS NEED REFINEMENT

Many materials and tooling concepts exist throughout industry, each having been developed by the manufacturer based on his experience in producing certain types of components. Current tooling approaches utilize many intermediate steps to produce the final tool, thus adding to the cost. High-rate production tooling may require refinement in tooling materials and concepts in order to ensure high-quality reproducible components.

Secondary tooling materials such as vacuum bags, sealants, bleeder cloths, etc., are critical items in composite manufacture and can become very critical in high-rate production.

The trend toward higher curing temperature resin systems leads to the requirement for higher temperature tooling materials which will maintain their configurational stability.

J. CURING IS A MAJOR IMPEDIMENT TO HIGH-RATE PRODUCTION

There is high reliance on the autoclave for curing organic composites, due to its flexibility and ability to accept large mixed loads. However, the long cycle times associated with this type of curing facility are a serious obstacle to high-rate production without adding additional equipment. Independently heated and pressurized curing tools are also available but require manual labor for loading and unloading.

Production rates could be increased significantly if rapid curing resins were available which did not require autoclaves.

IV. RECOMMENDATIONS

A. ENHANCE TRAINING PROGRAMS

Adequate training for engineers, designers, manufacturing, tooling, and quality control personnel needs to be emphasized. Interaction between the various disciplines involved in manufacture of composites is essential and methods should be developed to ensure this interaction. In addition, the semi-skilled labor force needs to receive on-the-job training for an extensive period of time to become proficient in the various steps involved in composites manufacture.

B. DEVELOP IMPROVED MATERIALS TAILORED FOR AUTOMATION

Materials suppliers should be encouraged to reduce the cost of materials through innovative processing. They may also provide materials in kit form as near-net-shape preforms to reduce the operations at the fabricator. There is also a need for resins which cure rapidly, at low pressures and preferably at low temperatures. Resins with tailored cure rheology would allow them to be used in a "layup to full consolidation" process. The advantages of thermoplastic resin systems need to be exploited further by development of resins with lower melt temperatures and viscosities.

C. DEVELOP IMPROVED PROCESSING TECHNIQUES

In conjunction with the development of improved resins, improvements in processing methods should be undertaken to take advantage of the rapid curing or low-pressure curing systems. Also, attention should be paid to the development and use of intermediate products such as pultrusions, braided forms, and standard structural sections. The use of monitoring devices to control the processing is also a part of the process development. Control criteria need to be developed in conjunction with the design requirements and manufacturing equipment capability.

D. DEVELOP PROTOTYPE EQUIPMENT BEFORE STARTING PRODUCTION

Higher rate production equipment for any given system requires a period of development and redesign before being placed in service as a production machine. Equipment manufacturers should be involved at the initial stage of component design to provide practical guidance on equipment limitations. Special processes and equipment need to be developed for small components.

It is strongly recommended that equipment development be recognized as an important prerequisite to production and that it should be undertaken as a separate and distinct entity with appropriate funding provided. Part of this effort should consist of a demonstration through manufacture of one or more typical components.

E. STANDARDIZE CERTAIN ELEMENTS IN COMPOSITES TECHNOLOGY

To increase the use, reduce the cost, and improve the reliability of composites, certain parts of the composites technology need to be standardized, especially materials and product forms, test methods, qualification procedures and criteria, and design data. Standardization is also needed for high rate production. Such an effort requires the cooperation of suppliers, fabricators, and users.

F. DEVELOP DESIGN PHILOSOPHY APPROPRIATE TO AUTOMATION OF DESIGN AND MANUFACTURE OF COMPOSITES

Design options of sheet/stringer, sandwich, or composite laminates for lightweight structures should be given proper consideration through trade-off studies before committing to any particular design philosophy for production. New design approaches need to be developed to solve problems with corrosion resistance and impact damage resistance in some composite designs.

In high-production-rate processes, it is imperative that the design is developed for automation of the manufacturing, quality control, and inspection processes.

G. EXPLOIT USE OF COMPUTER TECHNOLOGY IN ALL ASPECTS OF COMPOSITE DESIGN, MANUFACTURE, AND TESTING

Computer assistance should be fully utilized in the design of optimum structural integrity, producibility, development of fiber placement procedures, layout, cutting, and sequencing of plies, control of curing, development of tool design, inspection methods, and many other applications.

H. DEVELOP ACCEPTANCE CRITERIA

The effect of defects on the performance of composites needs to be well studied and documented to reduce the conservatism in design approaches now being employed.

I. IMPROVE TOOLING DESIGN

Tooling design philosophy should be directed toward to use of fewer tools, better materials, and simpler fabrication and assembly operations.

APPENDIX A

EDITED COMMENTS ON NONDESTRUCTIVE TESTING METHODS

APPENDIX A
EDITED COMMENTS ON NONDESTRUCTIVE TESTING METHODS

20 April 88

Mr. Ferrel Anderson, AMXIB-PA
Chairman, Steering Committee
DOD Composite Man: facturing
U.S. Army Industrial Engineering Activity
Rock Island, IL 61299-7260

Dear Ferrel:

I have studied the FIVE YEAR PROGRAM PLAN (1990-1994) which you enclosed with your letter of 5 April and have made the following comments:

> X-ray Tom-graphy - Page 42 - One of the major drawbacks to this method of x-ray inspection is its low resolution as compared to film radiography. MCAIR uses radiography to detect cracks, crazing, and linear porosity in the radii of integral stiffeners, angles, channels, zees and other associated structures. These flaws are significantly smaller than the minimum resolvable condition which tomographic techniques can detect. Currently, normal resolution in this type system is of the order of 1 mm and state of the art is 0.1 mm, while crack and crazing width in carbon/carbon, carbon/epoxy, and carbon/bismaleimide is of the order of 0.01 mm. Filmless techniques of x-ray inspection of composites are improving; but at the current time, do not come close to film techniques for inspection of composite structure of the types being discussed.
>
> Acoustic Emission - Page 42 - To date, our experience is that this technique is limited to simple structures like pressure vessels, monolithic skins, etc. If the test item has closures, integral stiffeners, variable thicknesses, etc., interpretation of the data is impossible without testing and dissecting significantly large numbers of parts or coupons in order to gain the necessary data required for the interpretation. Even then, normal manufacturing variances tend to produce enough variations in the emissions to preclude a reasonable interpretation from one part to the next. Examples of variances in composite assemblies to which I refer are skins thicknesses,

extra adhesive, resin runs, extra sealant, selection of fasteners and their amount of torque or whether they are installed wet or dry, etc.

Eddy Current - Page 42 - We have successfully linked eddy current probes to our ultrasonic C-scan systems to perform inspection of large-scale parts in relatively short time intervals. Initial inspections were performed on low velocity impacted carbon/epoxy, but limited work here and at other aerospace companies on carbon/carbon materials indicates that the concept could be utilized for this material also. We have successfully detected cracks in carbon/epoxy 0.06 inches beneath the surface, crack size was of the order of 0.25 inches × 0.03 inches deep.

Carbon/Carbon - Page 44 - Initial carbon/carbon materials did have very high ultrasonic attenuation, as indicated. Recent advances in carbon/carbon manufacturing methods are yielding high density (densified and often doped with inhibitors to decrease loss of properties due to exposure at high temperatures) materials which have ultrasonic attenuation of the same order as carbon/epoxy and carbon/bismaleimide laminates. In fact, we have used the same reference standards made of carbon/epoxy to calibrate our ultrasonic systems to inspect carbon/carbon, carbon/epoxy, and carbon/bismaleimide laminates and find very little, if any, difference in sound transmission. We do try to avoid using water as a couplant for carbon/carbon inspections due to its deleterious effect on the carbon/carbon. Also, it is good to avoid use of any liquid couplant since it tends to be absorbed into the laminate and thus mask porosity if present. The water in the pores does not inhibit ultrasound passage through the part.

Eddy current techniques can be used to determine loss in material density since density and conductivity tend to vary proportionately. Also, eddy current techniques can be used to measure the thickness and/or determine the presence of surface treatments such as silicon/carbide since these materials tend to be dielectrics when compared to the carbon/carbon. The technique for determining the coating thickness is a simple lift-off type measurement and can be calibrated using paper or plastic shims to establish a lift-off correlation. Only a bare specimen of the carbon/carbon is needed with the shims to perform calibration.

Holography - Page 43 - Our experience to date with holography is that it, like acoustic emission, is affected significantly by part geometry. Complex shaped parts are nearly impossible to interpret by this technique. We have found that holograms have all types of fringe patterns when in the vicinity of closures, integral stiffeners, internal backing materials, changes in section thickness, etc. These fringe patterns tend to inhibit meaningful interpretation in these areas. We had little difficulty finding flaws in simple geometry monolithic skins and honeycomb assemblies; but as soon as internal structure was varied, new fringe patterns resulted. Shop variations which were acceptable to part application such as extra adhesive, resin runs in cells, an extra composite ply, etc., caused anomalous fringe patterns which made interpretation nearly impossible or impossible.

I will be happy to critique any other workshop documents and will act on them in an expeditious manner. Please pass my apology on to others at the conference whom I may have inconvenienced due to my absence and don't forget to include me in any future workshop activities of this type.

Sincerely,

Kenneth L. Kremer
ASNT Certified Level III in PT, MT, UT, RT, LT
5803 Amberway Drive
St. Louis, MO 63128
314-777-5831

NDE COMMITTEE SUMMARY

The NDE representatives from industry and Government participated with the Workshop panels and held an after hours meeting to receive additional inputs from attendees. Conclusions and recommendations of the NDE committee are primarily a reiteration of the MTAG Test and Inspection Subcommittee report of September, 1987. We recommend additional periodic Workshops and resolution of the following areas of concern.

CONTRACT REQUIREMENTS

DoD contracts must contain first tier requirements for compliance with the Government specifications and standards which are necessary for program control and prevention of in-service performance risks. Product oriented surveys, program reviews, component failure investigations and accident investigations have frequently identified the omission of contractual requirements for NDT/I. Other lessons learned are not necessarily covered by Government specifications and standards, in these cases specific remedial measures, additional requirements, must be included in the contract. Examples which fall into this catagory are porosity severity determinations, detection and rejection of foreign included material and inspection of machined edges of composite materials.

MRB RECORD RETENTION

Another important area is record retention requirements for NDT/I related MRB actions. For traceable flight and maintenance critical components these records should be a contract deliverable. Proper age exploration maintenance of composite components is not possible without the production MRB records. Aircraft manufacturers routinely fabricate composite components which contain delaminations, voids, inclusions and porosity which exceed specified rejection criteria. Through engineering evaluation and material review board actions the rejectable components are typically accepted "as is" or accepted with repair. Since the DoD has limited long term experience with this technology, an in-service tracking system should be established to validate the accuracy of specification deviations. A reasonable sample number of the various types of material review report anomalies should be tracked to establish the longterm accuracy of production MRB actions. This would contribute to the effects of defects information which is being generated by numerous sample test programs.

PREVIOUS PROGRAMS SUMMARY

Many of the findings and recommendations from the February, 1986 DoD Composite NDE Technology Enhancement Program Planning Workshop deserve to be repeated.

COORDINATED EFFORTS

Optimized quality and inspection capability will be realized through an up-front coordinated effort by design, quality, production, materials and inspection.

STATISTICAL TECHNIQUES

The application of appropriate techniques to guarantee batch-to-batch consistency of prepregs and quality control measures during manufacture promise to solve many problems associated with the processability and reliability of composites. Quality and cost effective production are possible through statistical techniques which can be used to monitor and adjust the process on a periodic basis to minimize the possibility of producing unacceptable products.

MATERIALS SCIENCE BASE

The establishment of a "materials science base" that relates incoming materials characterization with composite fabrication, inspection and critical engineering properties/final product performance. This would allow us to fabricate reliable/optimized composite structures and reduce scrap rate by tailoring the manufacturing process to known variations in the starting materials.

FLAW CRITICALITY

Current defect criticality criteria for composite structures are at best semi-quantitative and by no means optimized. A significant level of effort involving both NDI and composite fracture mechanics research is indicated if the current existing highly conservative flaw cititcality criteria are to be replaced with more cost effective ones.

ULTRASONIC TECHNIQUES

Conventional ultrasonic techniques are currently adequate for the detection of critical delaminations in most autoclave processed materials consisting of a single type of composite. However, hybrid structures, repaired structures and fiber wound structures are frequently quite attenuating and may require the use of lower frequency through transmission or more complex ultrasonic systems and in extreme cases even these may not be adequate. Since it is not obvious that other techniques will be able to replace ultrasonics for this purpose in the near future, it is important that inspectability be required in design and fabrication of composite structure. With ultrasonic inspection, complicated mode conversion and reflections in irregularly shaped parts can easily confuse attempts at flaw detection. The problems of ultrasonic inspection are further compounded by the tendency of flaws to be most critical where geometry changes are most abrupt, such as at stress concentrators including corners, edges, and fastener holes. Acoustic wave propagation can become exceedingly complicated because of anisotropy, phase cancellation, highly localized variations in attenuation and signals can be distorted by frequency dependent velocity or attenuation. Inspection of thick sections can be a problem. Present ultrasonic instrumentation frequently lacks the necessary gain to test for flaws in such situations. Towards this end, alternative methods of generating and receiving ultrasound must continue to be persued. Time delay spectrometry is one potential solution which achieves both the gain efficiency of continuous wave excitation while preserving the depth discrimination capability of conventional pulse excitation.

SURGE CAPABILITY

Surge capability should be possible through high speed automated inspection equipment, raw material and processing control, sample inspection plans, and the development of realistic accept/reject criteria.

FIVE YEAR PLAN

The NDE Committee members agree with the five year program plan which was recommended by the DoD Composite NDE Technology Enhancement Program Planning Workshop in February 1986.

Gwynn K. McConnell

GWYNN K. MCCONNELL
COMMITTEE CHAIRMAN

APPENDIX B

LIST OF ATTENDEES AND WORKSHOP PRINCIPALS

DoD WORKSHOP ON THE MANUFACTURING/PRODUCIBILITY OF ORGANIC-MATRIX COMPOSITES, 12-14 APRIL, 1988

MR FERREL E ANDERSON
INDUSTRIAL BASE ENGINEERING ACTIVITY
INDUSTRIAL ENGINEER
AMXIB-PA
ROCK ISLAND IL 61299-7260
(309)782-5617

MR ROBERT G ANDERSON
BELL HELICOPTER TEXTRON, INC
MFG TECH
CHIEF, OPERATIONS PRODUCIBILITY
PO BOX 482
FORT WORTH TX 76101-0001
(817) 280-3247

MR DAVID R BEELER
US AIR FORCE
NON-METALS/COMPOSITES
TECHNICAL AREA MANAGER
AFWAL/MLTN
WRIGHT-PATTERSON AFB OH 45433-6533
(513) 255-7277

MR TERRY M BOUSTEAD
SIKORSKY AIRCRAFT
COMPOSITE PRODUCTS
CHIEF, TOOL DESIGN
6900 MAIN ST
STRATFORD CT 06601-1381
(203) 381-6122

MR JAY BRENTJES
LAWRENCE LIVERMORE NAT'L LAB
M/S 1342
GROUP LEADER COMPOSITES
PO BOX 808
LIVERMORE CA 94550-0001
(415)422-7038

DR PHILLIP M BROUDY
NAVAL INDUSTRIAL RES SUPPORT ACT
SUPRY GEN ENGR
BLDG 75-2, NAVAL BASE
PHILADELPHIA PA 19112-5078
(215)897-6683

DR CHARLES E BROWNING
US AIR FORCE
STRUCTURAL MTRL BRCH
CHIEF
AFWAL/MLBC
WRIGHT-PATTERSON AFB OH 45433-6533
(513)255-9070

MR STEVEN J BURPO
MCDONNELL AIRCRAFT CO
SR ENGR-APLS PROJ LEADER
BLDG 271D/1/M12
PO BOX 516
ST LOUIS MO 63166-0001
(314) 233-8874

MR BRIAN M BUTLER
NORTHROP CORPORATION
DEPT 3750/89
MGR
ONE NORTHROP AVE
HAWTHORNE CA 90250-0001

MR PETER W BZDAK
DOD DLA
DPESO
PROJECT ENGR
CAMERON STATION
ALEXANDRIA VA
(703) 756-8994

MR FLAKE CAMPBELL
MCDONNELL AIRCRAFT CO
DEPT 813A
DIR MFG RES ENGR, ADV MFG BAFR FAC
PO BOX 516
ST LOUIS MO 63166-0516
(314) 234-5942

MR RICHARD CELIN
NAVAL AIR ENGRG CTR
MECH ENGR
CODE 124
LAKEHURST NJ 08733-5100
(201)323-2423

MR STANLEY L CHANNON
CONSULTANT
2361 DAVENTRY RD
RIVERSIDE CA 92506-0001

MR LEE F CHOQUETTE
ICI/FIBERITE
ENGRG & DESIGN TOOL/RITE
STE A
23271 VERDUGO
LAGUNA HILLS CA 92653-1347
(714)472-4227

MR EUGENE G CROSSLAND
BOEING ADV SYSTEMS
MGR MTLS & MFG TECH
M/S [illegible]
PO BOX 3707
SEATTLE WA 98124-2207
(206)241-4437

MR BOB DANIELS
NAVAIR
AIR 5142D3
PRODUCTION MGMT PROJ OFFICER
1235 JEFF DAVIS HWY
WASHINGTON DC
692-4868

MR ARTHUR DEISSLER
GRUMMAN AIRCRAFT SYSTEMS
MGR
M/S 818-002
SO OYSTER BAY RD
BETHPAGE NY 11714-3582
(516)575-9458

MR PETER DIXON
BOEING HELICOPTER
MGR MFG R&D
PO BOX 16858
PHILADELPHIA PA 19142-0001
(215) 591-3643

MR DONALD J DORR
MCDONNELL AIRCRAFT
DEPT 390/BLDG 270C/RM 21C
CHIEF ENGR
PO BOX 516
ST LOUIS MO 63166-0001
(314) 232-3066

MR FRANK H DOYAL
TEXTRON AEROSTRUCTURES
DIR ENGRG DESIGN & DEV
PO BOX 210
NASHVILLE TN 37202-0001
(615)361-2909

MR ROBERT K FOGG
NAVAL OCEANS SYSTEMS CTR
SUPR STRUCTURAL MTLS SCI
CODE 932
271 CATALINA BLVD
SAN DIEGO CA 92152-5000
(619)553-3219

MR TOM D GAFFNEY
BOEING COMMERCIAL AIRCRAFT
DESIGN GRP MGR
M/S 79-60
PO BOX 3707
SEATTLE WA 98124-2207
(206)234-2964

MR BOB GARZA
MCDONNELL DOUGLAS
HELLICOPTER CO
MFG R&D ENGR SR
5000 EAST MCDOWELL
MESA AZ 85205-0001
(602)891-5084

MR DAVID C GIBSON
LOCKHEED AERONAUTICAL SYSTEMS CO
DEPT 93-20 ZONE 457
V-22 PROG MGR
86 SOUTH COBB DR
MARIETTA GA 30060-0001
(404) 494-2931

MR W. BRANDT GOLDSWORTHY
GOLDSWORTHY ENGINEERING, INC
PRESIDENT
23950 MADISON ST
TORRANCE CA 90505-6085
(213) 373-6875

DR WILLIAM S HONG
INST FOR DEF ANALYSES
SCIENCE & TECHNOLOGY DIV
RES STAFF MBR
1801 N BEAUREGARD ST
ALEXANDRIA VA 22311-0001
(703)578-2826

MR RUDY GONZALEZ
NORTHROP
MGR/NONMETALLICS MTLS & PROC
8900 E WASHINGTON BLVD
PICO RIVERA CA 90660-3737
(213) 942-5540

MR JACK HURD
US ARMY
GEN ENGR
AMCPD-BD
5001 EISENHOWER AVE
ALEXANDRIA VA 22333-0001
(202)274-8289

MR ALAN R GOODWORTH
MCDONNELL DOUGLAS
HELICOPTER CO
SR MTS ADV STRUCTURES DESIGN
5000 EAST MCDOWELL RD
MESA AZ 85205-9797
(602) 891-6530

MR GEORGE E HUSMAN
BSAF STRUCTURAL MATERIALS INC
VP BUS DEV
11501 STEELE CREEK BLVD
PO BOX 7687
CHARLOTTE NC 28217-9998
(704)529-8236

MR DANA M GRANVILLE
US ARMY MATERIALS TECHNOLOGY LAB
MTLS ENGR
SLCMR-OC
BLDG 39 ARSENAL ST
WATERTOWN MA 02172-0001
(617)923-5172

MR GERALD C JANICKI
DOUGLAS AIRCRAFT CO
BRANCH MGR MFG R&D
M/S C1-655/1-22
3855 LAKEWOOD BLVD
LONG BEACH CA 90846-0001
(213)593-8390

MR JOHN B HAMMOND
LOCKHEED CORP
CHIEF STRUCTURES ENGR
HOLLYWOOD WAY
PO BOX 551
BURBANK CA 91520-0001
(818) 847-1048

MR JOE F JONES
LOCKHEED AERONAUTICAL SYSTEMS CO
DEPT 70-05 BLDG 369 P/B-6
CHIEF ENGR-TECH
PO BOX 551
BURBANK CA 91520-7911
(818) 847-7911

MR MARLYN F HARP
BOEING MILITARY AIRPLANE CO
M/S K76-67
MGR MTLS & PROCESSES TECH
PO BOX 7730
WICHITA KS 67277-7730
(316) 221-3207

DR KARL C KAUFFMAN
NAVAL WEAPONS CENTER
RES CHEMIST
CODE 3624
CHINA LAKE CA 93555-6001
(619)939-1305

MR LARRY G KELLY
US AIR FORCE
BRANCH CHIEF
AFWAL/FIBC
WRIGHT-PATTERSON AFB OH 45433-6533
(513) 255-4030

MR HENRY M MCILROY
ALLIED-SIGNAL AEROSPACE CO
MTGS ENGRG
SR PROJECT ENGR
PO BOX 419159
KANSAS CITY MO 54141-6159
(816)997-4171

MR TIMOTHY KINSELLA
GENERAL DYNAMICS
SUPR NDE
PO BOX 748
MAIL ZONE 6481
FORT WORTH TX 76101-0001
(817) 777-8643

MR DANIEL P MCILROY
BELL HELICOPTER CO
CHF TOOL ENGR
600 E HURST BLVD
HURST TX 76053-0001
(817)280-2833

MR TRENT R LOGAN
ROCKWELL INTERNATIONAL
MGR ADV STRUCTURES
201 N DOUGLAS
PO BOX 92098
LOS ANGELES CA 90001-0001
(213) 647-6416

MR LEE MCKAGUE
GENERAL DYNAMICS CORP
ENGRG CHIEF
MZ 2163
PO BOX 748
FORT WORTH TX 76101-9990
(817) 777-2126

MR RAY LUKEN
NAVAL AIR SYSTEMS COMMAND
MTLS ENGR
CODE 5304C2
WASHINGTON DC 20361-5000
(202) 692-6025

MR MARTIN J MCLAUGHLIN
NORTHROP CORP
MGR
M/S 5077/96
ONE NORTHROP AVE
HAWTHORNE CA 90250-3277
(213)416-3822

MR L. THOMAS MAZZA
AVIATION APPLIED TECHNOLOGY DIRECTORATE
AERO ENGR
SAVRT-TY-ATS
FORT EUSTIS VA 23604-5577
(804) 878-2377

MR JAMES M MCVICAR
SIKORSKY AIRCRAFT
MGR-AIRFRAME SYSTEMS DESIGN
MS S309A
6900 MAIN ST
STRATFORD CT 06601-1381
(203) 386-7498

GWYNN K MCCONNELL
NAVAL AIR DEVELOPMENT CTR
NDT/I SUPPORT COORDINATOR
CODE 6063
WARMINSTER PA 18974-5000
9215) 441-1772

MR JOHN MEANEY
ROHR INDUSTRIES
SR PROJ ENGR
FOOT OF H STREET
CHULA VISTA CA 92012-0001
(619)691-3682

MR HERBERT E MERRITT
CINCINNATI MILACRON
MGR, TECH ASSESSMENT
4701 MARBURG AVE
CINCINNATI OH 45209-1086
(513) 841-8658

MR CHARLES P NEWTON III
LTV AIRCRAFT PRODUCTS GROUP
PROG MGR FLEXIBLE COMPOSITES CTR
IMOD/FCC
PO BOX 655907
DALLAS TX 75265-5907
(214) 266-0964

MR RALPH MILLER
LTV AIRCRAFT PRODUCTS
MGR MFG TECH
M/S 49L-15
PO BOX 655907
DALLAS TX 75265-5907
(214)266-4516

MR ROBERT L PINCKNEY
BOEING HELICOPTERS
MGR-SPECIAL PROJECTS
M/S P38-48
PO BOX 16858
PHILADELPHIA PA 19142-0001
(215) 591-8189

MR BARTON W MOENSTER
MCDONNELL AIRCRAFT CO
BRANCH MGR ADV MFG
BLDG 270C/2/210
PO BOX 516
ST LOUIS MO 63166-0001
(314) 233-0905

MR J T POLLARD
GENERAL DYNAMICS
ENGRG SPECIALIST SR
PO BOX 748
FORT WORTH TX 76101-0001
(817) 763-[illegible]

DR DANIEL R MULVILLE
NAVAL AIR SYSTEMS COMMAND
CODE RM
PROGRAM MGR FOR STRUCTURES
NASA HEADQUARTERS
WASHINGTON DC 20546-0001
(202) 453-2862

MR WALTER POTTHOFF
BOEING HELICOPTER
J-22 ENGRG
ENGRG MGR
MS P24-07
PO BOX 16858
PHILADELPHIA PA 19142-0001
(215) 591-8293

MR ROBERT M NEFF
US AIR FORCE
BRANCH CHIEF
AFWAL/MLTN
WRIGHT-PATTERSON AFB OH 45433-6533
(513)255-7277

MR JONATHAN PRATCHER
US ARMY
AVIATION SYSTEMS COMMAND
INDUS ENGR
4300 GOODFELLOW BLVD
ST LOUIS MI 63031-1798
(314)2[illegible]3-3079

MR RONALD M NEUFELD
BOEING ADV SYSTEMS
QUALITY ENGRG MGR
M/S 4E-85
PO BOX 3707
SEATTLE WA 98124-2207
(206)655-3728

MR JOHN QUIGLEY
ARMY MATERIAL COMMAND
AMCTD-PA
GEN ENGR
5001 EISENHOWER AVE
ALEXANDRIA VA 22333-0001
(202) 274-4434

MR JOHN QUINTON
BEECH AIRCRAFT
DEPT 40/839
GEN FOREMAN TOOLING
9709 EAST CENTRAL
PO BOX 85
WICHITA KS 67201-0001
(316) 681-8079

MR CHARLES W ROGERS
BELL HELICOPTER TEXTRON
DEPT 81
CHIEF LXH AIRFRAME DESIGN
PO BOX 482
FORT WORTH TX 76101-0001
(817) 280-2542

MR ROBERT E SANDERS
BELL HELICOPTER TEXTRON
DEPT 80, MS 19
GROUP ENGR-METHODS & MTLS LAB
PO BOX 482
FORT WORTH TX 76101-0001
(817) 280-3085

MR CECIL W SCHNEIDER
LOCKHEED GEORGIA CO
MGR COMPOSITES R&D
D/72-19 ZN 450
86 S COBB DR
MARIETTA GA 30063-0001
(404)494-3154

MR ROB J SJOSTEDT
GOLDSWORTHY ENGINEERING, INC
TECHNICAL DIR
23950 MADISON ST
TORRANCE CA 90505-6085
(213) 373-6875

MR ALLEN SOUTHMAYD
MCDONNELL AIRCRAFT CO
SECTION MGR
DEPT 121A, BLDG 245, POST W4
PO BOX 516
ST LOUIS MO 63166-0001
(314)232-8932

MR CHARLES W STAFFORD
BOEING HELICOPTERS
TOOLING & PLANNING MGR
PO BOX 16858
PHILADELPHIA PA 19142-0001
(215)591-2389

MR GARY N STEVENSON
GENERAL DYNAMICS CO
MAIL ZONE 6492
CHIEF ADV TECH DEV
PO BOX 748
FORT WORTH TX 76101-0748
(817) 777-5077

MR ROBERT H STONE
LOCKHEED-BURBANK
RES SPECIALIST SR
BLDG 369/B-6
PO BOX 551
BURBANK CA 91520-7637
(818)847-7901

DR SAAD TAHA
ROCKWELL INTERNATIONAL
M/S GC13
PROG MGR
PO BOX 92098
LOS ANGELES CA 90009-0001
(213) 647-6964

MR FRED W TERVET
LOCHEED AERONAUTICAL SYS CO
DEPT 47-17 BLDG 369 PLANT B-6
MFG RES GROUP ENGR
PO BOX 550
BURBANK CA 91520-4717
(818) 847-3800

MR PAUL A VALLIER
SIKORSKY AIRCRAFT
MS 8-700
OPERATIONS MGR, COMPOSITE PROD
6900 MAIN ST
STRATFORD CT 06601-0001
(203) 381-6164

MR SAMUEL E VAN HORN
TELEDYNE RYAN AERONAUTICAL
DIRECTOR
2701 HARBOR DRIVE
PO BOX 85311
SAN DIEGO CA 92138-5311
(619) 260-4398

MR ROBERT VAN SICLEN
LTV MISSELS & ELECTRONICS
MS EM6)
PROGRAM MGR
PO BOX 650003
DALLAS TX 75265-0003
214/266-7867

MR GARY F VAN Y
GENERAL DYNAMICS CORP
MGR ADV MFG TECH
M/S 6490
PO BOX 748
FORT WORTH TX 76101-0001
(817) 777-5068

MR JOHN C WEIDNER
HERCULES AEROSPACE
M/S 2422U
MANAGER
PO BOX 98
MAGNA UT 84044-0098
(801) 251-3322

MR RAY T WILLIAMS
FIBERITE/ICI
STE A
MKTG MGR
23271 VERDUGO
LAGUNA HILLS CA 92653-1347
(714)472-4227

DoD COMPOSITES MANUFACTURING/PRODUCIBILITY WORKSHOP
PANEL SESSIONS CO-CHAIRMEN AND STEERING COMMITTEE MEMBERS

WORKSHOP CHAIRMAN

Mr. Ferrel E. Anderson
Industrial Engineering Activity
ATTN: AMXIB-PA
Rock Island, Il 61299-7260
309/782-6226, AV 793-6226

DEPARTMENT OF DEFENSE SPONSOR

Mr. Kenneth Foster
The Pentagon, Room 3C257
Washington, D.C. 20301
202/695-7580, AV 224-4783

PANEL SESSIONS

DESIGN PANEL

Government Co-Chairman:

Mr. Larry Kelly
AFWAL/FIBC
Wright-Patterson AFB, OH 45433
513/255-4030, AV 785-4030

Industry Co-Chairman:

Mr. Charles Rogers
Bell Helicopter Textron
PO Box 482
Dept. 81, Mail Drop 4
Fort Worth, TX 76101
817/255-4030

MATERIALS AND PROCESSING PANEL

Government Co-Chairman:

Mr. Charles F. Browning
AFWAL/MLBC
Wright-Patterson AFB, OH 45431
513/255-9070, AV 785-9070

Industry Co-Chairman:

Mr. Flake Campbell
McDonnell Aircraft Co
PO Box 516
Dept. 113A, Bldg. 276/1/A27
St. Louis, MO 63166
314/234-5942

MATERIAL LAY-UP AND ASSEMBLY PANEL

Government Co-Chairman:

Mr. Tom Mazza
Aviation Applied Technology
Directorate (AVSCOM)
ATTN: SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
804/878-2377, AV 927-2377

Industry Co-Chairman:

Mr. Robert Anderson
Bell Helicopter Textron
Dept 85 Manufacturing Engrg
PO Box 482
Fort Worth, TX 76101
817/280-3247

TOOLING PANEL

Government Co-Chairman:

Mr. Dave Beeler
AFWAL/MLTN
Wright-Patterson AFB, OH 45433-6533
513/255-7277, AV 785-7277

Industry Co-Chairman:

Mr. Cecil W. Schneider
Lockheed-Georgia Div.
86 S. Cobb Drive
D/72-19 Zn 450
Marietta, GA 30063-0001
404/424-3154

STEERING COMMITTEE MEMBERS

CHAIRMAN

Mr. Ferrel Anderson
Industrial Engineering Activity
ATTN: AMXIB-PA
Rock Island, IL 61299-7260
309/782-6226, AV 793-6226

Dr. P.M. Broudy
Naval Material Command
Naval Industrial Resource Spt. Actvy
Code 20, Bldg. 75-2 Naval Base
Philadelphia, PA 19112-5078
215/897-6683, AV 443-6683

Mr. Stanley L. Channon
Consultant IDA
2361 Daventry Road
Riverside, CA 92506
714/683-7357

Mr. Kenneth Foster
The Pentagon, Room 3C257
Washington, D.C. 20301
202/695-7580, AV 224-4783

Dr. John Hove
Institute for Defense Analyses
1801 N. Beauregard St
Alexandria, VA 22311
703/578-2869

Mr. Robert Neff
Air Force Wright Aeronautical Lab
ATTN: AFWAL/MLTN
Wright-Patterson AFB, OH 45433-653
513/255-7277, AV 785-7277

APPENDIX C

WELCOME ADDRESS
BY
KENNETH J. FOSTER (OUSDA)

WELCOME TO THE DOD WORKSHOP ON COMPOSITE MATERIALS. WE ARE CONDUCTING THIS WORKSHOP WITH THE CONCERN AND CONSENT OF THE UNDERSECRETARY OF DEFENSE FOR ACQUISITION, DR. ROBERT COSTELLO, WHO IS ON TRAVEL TODAY.

DR. COSTELLO HAS SEVERAL INITIATIVES WHICH HE HAS PUT FORTH FOR NEW FOCUS AND EMPHASIS. OF THOSE INITIATIVES, HIS FIRST PRIORITY FOR THE DEPARTMENT OF DEFENSE IS THE DEVELOPMENT AND MAINTENENCE OF AN INDUSTRIAL BASE SUFFICIENT TO MEET THE DEFENSE NEEDS OF THE UNITED STATES. SUFFICIENCY IN THIS RESPECT MEANS THAT ENOUGH INDUSTRIAL CAPABILITY IS AVAILABLE TO MEET THE PEACETIME DEFENSE NEEDS, ENOUGH TO MEET A WARNING OR INTERIM BUILD-UP TIME, AND ENOUGH TO MEET POTENTIAL WARTIME NEEDS. THAT KIND OF SUFFICIENCY CAN BE VIEWED IN SEVERAL WAYS.

FIRST, WE CAN LOOK AT SUFFICIENT ACCESS TO RAW MATERIALS AND ENERGY TO SUPPLY AND FUEL OUR BASIC INDUSTRIAL STRUCTURE. SECOND, WE CAN LOOK AT INDUSTRIAL CAPACITIES TO MEASURE SPECIFIC PRODUCTION, TOTAL INDUSTRIAL OUTPUT, THE MILITARY DEMAND SCENARIO AND WHATEVER CIVILIAN AUSTERITY MAY BE POSTULATED. THIRD, WE CAN LOOK AT RELATIVE TECHNOLOGIES FOR WEAPON SYSTEM ADVANTAGES ON THE BATTLEFIELD AT ANY GIVEN TIME. AND, WE CAN LOOK AT NATIONAL AND INTERNATIONAL STRATEGIES BOTH FROM OUR OWN PERSPECTIVE AND THOSE WE BELIEVE OUR ADVERSARIES HAVE DEVELOPED. THEN, WITH ALL THIS, WE PLAN, POSTULATE AND PREPARE. THE MILITARY OBJECTIVE IS READINESS.

FUNDAMENTALLY, FROM AN INDUSTRIAL READINESS POINT OF VIEW, WHETHER IN PEACETIME OR IN WAR, OUR OBJECTIVE IS TO PROVIDE THE MILITARY FORCES WITH THE BEST MILITARY HARDWARE WE CAN DEVELOP, MANUFACTURE AND FIELD. THEN, WE MUST SUSTAIN SUFFICIENT PRODUCTION OF THAT HARDWARE DURING BOTH PEACETIME AND ANY NATIONAL EMERGENCY. THAT BASIC OBJECTIVE IS BECOMING INCREASINGLY MORE DIFFICULT TO ACHIEVE.

DURING WWII, THE UNITED STATES INDUSTRIAL BASE PRODUCED 310,000 AIRCRAFT, 88,000 TANKS, 10 BATTLESHIPS, 358 DESTROYERS, 211 SUBMARINES, 27 AIRCRAFT CARRIERS, 411,000 ARTILLERY TUBES AND HOWITZERS, 12,500,000 RIFLES AND CARBINES, AND 900,000 TRUCKS AND MOTORIZED WEAPONS CARRIERS. THAT WAS

AWESOME INDUSTRIAL CAPABILITY. DURING MARCH, 1944, THE UNITED STATES PRODUCED 9,117 MILITARY AIRCRAFT. IN THE SAME MONTH, 1,600 ALLIED AIRCRAFT WERE USED TO CONDUCT THE FIRST SUCCESSFULL BOMBING OF BERLIN. MY POINT HERE IS NOT THE JUSTIFICATION OF ANY MILITARY STRATEGY. MY MESSAGE IS MORE FUNDAMENTAL.

WE NO LONGER HAVE THE CAPACITY TO PRODUCE AIRCRAFT IN THOSE NUMBERS NOR DO WE HAVE SUCH MISSIONS ENVISIONED IN OUR NATIONAL STRATEGY. HOWEVER, THE MASS PRODUCTION CAPABILITY OF THE UNITED STATES THAT EXISTED FORTY-FOUR YEARS AGO HAS BEEN REPLACED BY A 70% SERVICES ECONOMY. MUCH HAS CHANGED.

MANY MILITARY AND INDUSTRIAL TECHNOLOGIES HAVE ALSO CHANGED. FORTY-FOUR YEARS AGO, MILITARY AIRCRAFT WERE MADE OF METAL, USED RECIPROCATING ENGINES, FIRED MACHINE GUNS AND DROPPED IRON BOMBS. TODAY, WE USE DIFFERENT MATERIALS IN AIRCRAFT STRUCTURES, POWER WITH GAS TURBINES, USE PRECISION GUIDED MUNITIONS AND ALSO HAVE A VARIETY OF PAYLOAD WEAPONS RANGING FROM CRUISE MISSILES, TO LASER GUIDED BOMBS TO VARIOUS NUCLEAR DEVICES.

NATIONAL STRATEGIES HAVE ALSO CHANGED. MILITARY HARDWARE HAS CHANGED. THE DOMESTIC INDUSTRIAL BASE HAS CHANGED. AND, SIGNIFICANTLY, THE DEVELOPMENT OF NEW TECHNOLOGIES HAS BEEN A LEADING INFLUENCE, SOMETIMES A DRIVING FORCE, OF VERY MUCH THAT HAS CHANGED.

MATERIALS TECHNOLOGY LED THE WAY FOR MUCH THAT HAS HAPPENED AND A GREAT DEAL OF WHAT WILL HAPPEN. OUR QUANTUM LEAPS FORWARD ARE OFTEN LINKED TO NEW DEVELOPMENTS AND USES OF NEW INDUSTRIAL MATERIALS. STEEL PAVED THE WAY FOR IMPROVED SHIPS OVER WOOD AND PROVIDED THE ARMOR NEEDED BY TANKS TO OVERCOME TRENCH WARFARE TACTICS OF WW I. ALUMINUM MADE POSSIBLE THE AIRCRAFT OF WW II. COBALT IMPROVED THE TEMPERATURE CABABILITIES OF TURBINE ENGINES, DEPLETED URANIUM AFFORDED IMPROVED ARMOR PENETRATION CAPABILITIES. WE CAN GO ON.

IN HISTORY, SOCIAL CHANGES ARE ATTRIBUTED TO THE BRONZE AGE, LATER TO THE DISCOVERY AND BENEFITS OF IRON, THEN TO STEEL PRODUCTION ASSOCIATED WITH THE INDUSTRIAL REVOLUTION. MOST OF ALL THIS POINTED TO THE NEW AND REVOLUTIONARY USES OF NEW METALS. QUITE FRANKLY, FOR THOSE OF US

WITH MANUFACTURING BACKGROUNDS, METAL PLAYED THE DOMINANT ROLE IN HOW TO PRODUCE SOMETHING OR WHAT TO PRODUCE, WHETHER ONE WAS RELATING TO CAPITAL EQUIPMENT OR THE FINAL PRODUCT. METAL HAS DOMINATED MANUFACTURING AS THE PRIMARY MATERIAL.

THEN, CAME THE NEW WORD -- PERFORMANCE. DURING WW II, WE HAD DONE JUST ABOUT ALL WE COULD WITH AIRCRAFT AS THEY WERE KNOWN AT THAT TIME. THE POST WW II BREAKTHROUGH WAS KNOWN AS THE JET AGE AS ASSOCIATED WITH TURBINE ENGINES AND USE OF A NEW METAL FOR AIRFRAMES. THE NEW METAL WAS TITANIUM WHICH WAS NOT MUCH MORE THAN A LABORATORY CURIOSITY UNTIL THE KOREAN WAR ERA. WE SQUEEZED WHAT WE COULD OUT OF THOSE TWO TECHNOLOGIES FOR ABOUT TWO DECADES.

MEANWHILE, AN EVOLUTIONARY MATERIALS DEVELOPMENT WAS UNDERWAY. SOMETHING NEW WAS NEEDED TO FURTHER EXTEND RANGE, REDUCE FUEL CONSUMPTION, AND INCREASE PAYLOAD CARRYING CAPABILITY. ONCE AGAIN, A DEPARTURE FROM TRADITIONAL TECHNOLOGIES WAS NECESSARY TO ACHIEVE IMPROVED PERFORMANCE.

COMPOSITES. TODAY'S EVOLUTION IN STRUCTURAL DESIGN OF NEW MILITARY AIRCRAFT IS INTEGRALLY LINKED WITH COMPOSITES. IN FACT, EVERY FORESEEABLE GENERATION OF COMBAT AIRCRAFT, STRATEGIC MISSILE SYSTEM AND SELECTED SPACECRAFT IS EXPECTED TO USE COMPOSITE MATERIALS IN SOME FORM. THE USE OF COMPOSITE MATERIALS IN THE PRODUCTION OF AIRCRAFT MAY BE CALLED THE STATE-OF-THE-MATERIALS-ART. THE USE OF MODERN MANUFACTURING TECHNIQUES TO PRODUCE COMPOSITE AIRCRAFT STRUCTURES, HOWEVER, HAS NOT PROGRESSED BEYOND THE MANUAL MODE. THERE ARE A NUMBER OF REASONS FOR LACK OF MECHANICAL MANUFACTURING PROGRESS USING COMPOSITE MATERIALS SUCH AS LOW PRODUCTION RATES FOR AIRCRAFT, AFFORDABILITY, LACK OF RETURN-ON-INVESTMENT INCENTIVES AND OTHERS I AM SURE.

WE ARE NOT HERE TO TRY TO SOLVE ALL THE ISSUES INVOLVED WITH MANUFACTURING USING COMPOSITE MATERIALS. THERE ARE SIMPLY TOO MANY VARIABLES. IF PRODUCTION RATES HAD BEEN HIGHER OVER THE PAST TEN YEARS, WE PROBABLY WOULD HAVE PASSED THE THRESHHOLD OF AFFORDABILITY AND JUSTIFIED THE INVESTMENTS NEEDED TO PROCEED PAST HAND LAY-UP INTO SOME KIND OF AUTOMATED MODE OF MANUFACTURING. WHETHER IT BE

CHEMICAL, MECHANICAL OR A COMBINATION OF BOTH. BUT, THAT MANUFACTURING PROGRESS HAS NOT HAPPENED.

HOWEVER, AT THIS JUNCTURE, WE DO STAND BEFORE A SIGNIFICANT THRESHHOLD. ONE OF INCREASED USE OF COMPOSITE MATERIALS BY WEIGHT IN NEW AIRFRAMES PLUS A POTENTIAL INCREASE IN PRODUCTION RATES OF AIRCRAFT USING COMPOSITE MATERIALS. THE INCREASED USE OF COMPOSITES IS MORE BY FACTORS THAN PERCENTAGE. THE INCREASED PRODUCTION RATES MAY BE MORE BY PERCENTAGE THAN BY FACTOR. THE USAGE IS CONTROLLED BY DESIGN WHEREAS PRODUCTION RATES ARE CONTROLLED BY CONGRESSIONAL APPROPRIATIONS. NEVERTHELESS, THE RESULTANT VOLUME OF COMPOSITE MATERIALS USE IN AIRCRAFT STILL INCREASES BY FACTORS. MY ESTIMATES INDICATE MORE THAN A TEN-TO-ONE INCREASE IN COMPOSITES USE FROM THE EARLY 1980'S TO THE MID-1990'S.

MOREOVER, THE USE OF COMPOSITE MATERIALS IN A WIDE RANGE OF MILITARY HARDWARE IS MANIFEST BY THE FACT THAT MORE THAN $80 BILLION OF COMMITTED ACQUISITIONS ARE SCHEDULED TO USE COMPOSITE MATERIALS. THE DOLLAR AMOUNT IS A DELIBERATE OVERSTATEMENT SINCE IT IS THE AGGREGATED VALUE OF ALL THE WEAPON SYSTEMS INVOLVED AND NOT THE VALUE OF THE COMPOSITE MATERIALS. BUT, THE DOLLAR AMOUNT DOES INDICATE THE PERVASIVE USE OF COMPOSITE MATERIALS IN THE HARDWARE. THE SIGNIFICANCE IS THE EXPESSED COMMITTMENT OF THE MILITARY TO USE COMPOSITE MATERIALS WITH NO INTENTIONS OF RETURNING TO TRADITIONAL TECHNOLOGIES. THE SACRIFICE IN PERFORMANCE APPEARS UNACCEPTABLE FROM A MISSION-BASED PERSPECTIVE.

COMMITMENTS TO IMPROVED TECHNOLOGIES OFTEN HAVE THEIR PROBLEMS. IN THE CASE OF COMPOSITE MATERIALS, WE HAVE PROVEN THE VALUE OF THEIR USE IN ACHIEVING CERTAIN PERFORMANCE CHARACTERISTICS. BUT, EACH OF THE AIRFRAMES ARE VIRTUALLY HAND-MADE. AND, THE MANUAL MANUFACTURING TECHNIQUE IS DOMINANT AT PRODUCTION FACILITIES. FURTHERMORE, WE HAVE NO COLLECTIVE VIEW OR AGREEMENT OR PLAN ON HOW TO MAKE THE TRANSITION FROM HAND LAY-UP TO MECHANICAL MANUFACTURING.

MORE STRATEGICALLY, SINCE WE HAVE SIMILAR TECHNIQUES TO MANUFACTURE AIRFRAMES NOW, WE NEED A CONSORTIUM IN WHICH TO ADDRESS THE ISSUE OF PROVIDING THE AIRFRAME MANUFACTURING BASE FOR USING INCREASED COMPOSITE MATERI-

ALS IN THE FUTURE. IN ADDITION, WE MUST ADDRESS THE ISSUE OF BEING ABLE TO SURGE PRODUCE AIRFRAMES USING COMPOSITE MATERIALS DURING A NATIONAL EMERGENCY. AS YOU KNOW FROM THE COTTAGE INDUSTRY EXPERIENCE, HAND MANUFACTURING HAS A RELATIVELY FLAT PRODUCTION CURVE. MORE COTTAGES WERE NEEDED TO INCREASE TOTAL VOLUME. IN MODERN MANUFACTURING, INCREASED CAPACITY IS NEEDED TO PRODUCE AT PRODUCTION RATES ABOVE ANY GIVEN NORM. FURTHERMORE, IF WE WAIT UNTIL CONTRACTS ARE AWARDED FOR HIGHER COMPOSITE USE AIR FRAMES, SAY 60% TO 100%, OR FOR HIGHER PRODUCTION RATES, SAY 30 TO 40 AIRFRAMES PER MONTH, THEN WE HAVE A VERY LONG WAIT UNTIL MECHANICAL METHODS AND MACHINERY ARE PLANNED, DESIGNED, DEVELOPED, PRODUCED, AND DELIVERED TO THE FACTORY FLOOR FOR DIRECT USE. THAT TIME FRAME COULD BE SEVERAL YEARS LONG AND SHOULD NOT BE NECESSARY.

OUR WORKSHOP IS INTENDED TO HELP ALLEVIATE THAT TIME PERIOD. OUR WORKSHOP IS THE CONSORTIUM NEEDED. OUR OBJECTIVE IS CLEAR.

THE WORKSHOP CHAIRMEN, PARTICIPANTS, AND COLLECTIVE EXPERTISE ASSEMBLED HERE FOR THE NEXT THREE DAYS TO ADDRESS THE TWO OBJECTIVES ANNOUNCED ARE THE VERY BEST IN THE BUSINESS. EVERYONE HERE IS BY INVITATION AND THE DECISION TO KEEP THE INVITEE LIST "BY INVITATION ONLY" WAS DELIBERATE. COMPOSITE TECHNOLOGY IS VERY SPECIFIC AND THE OBJECTIVES ARE TOO IMPORTANT TO ALL OF US TO PERMIT ANYTHING LESS THAN EXCELLENCE. WE ARE HERE TO FACILITATE A TOP PRIORITY PROBLEM SOLVING EFFORT.

THE UNDERSECRETARY APPRECIATES THE FACT THAT YOU ARE DEVOTING YOUR TIME AND ENERGY TO HELP IN THIS EFFORT. THE ARMY, NAVY AND AIR FORCE ALSO APPRECIATE YOUR CONCERN AND PARTICIPATION.

WE ALL LOOK FORWARD TO THE RESULTS OF YOUR COMBINED EFFORT. WE LOOK TO THE ROADMAP FOR INCREASING COMPOSITE USE IN AIRFRAMES AND THE ABILITY TO SURGE AIRFRAME PRODUCTION RATES USING MECHANICAL MANUFACTURING TECHNIQUES. THAT IS THE KEY TO THE COMPOSITES INDUSTRIAL BASE OF THE MID 1990'S AND PRODUCTION SURGE CAPABILITIES DURING NATIONAL EMERGENCIES.

ONCE AGAIN. THANK YOU.